A. A. Blagonravov and Others, Editors

SOVIET ROCKETRY

SOME CONTRIBUTIONS TO ITS HISTORY

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Academy of Sciences of the USSR. Historical Institute for Natural Science and Engineering

A. A. BLAGONRAVOV AND OTHERS, EDITORS

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Some Contributions to its History

(Iz istorii raketnoi tekhniki)

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N66 37127

V.A. Tarasova

WORK ON ROCKETRY IN RUSSIA FROM THE SECOND HALF OF THE 19TH CENTURY DOWN TO 1917 (ACCORDING TO THE MATERIALS OF THE AIM ARCHIVE)*

(Raboty po raketnoi tekhnike v Rossii so vtoroi poloviny XIX v. do 1917g. (po materialam arkhiva AIM))

Achievements in rocketry in 19th century Russia are closely connected with the Petersburg Rocket Institute (PRZ) and its director Konstantin Ivanovich Konstantinov** (1817-1871), whose name was known in those years to many artillerymen in Russia and abroad.

On the basis of its experience in the production and application of military rockets in previous years, PRZ worked out and realized the most perfect designs of the time for solid-propellant rockets, and established the basic technology of their production by a range of new tools and machines. Test stand trials were the foundation of rocket ballistics. In the 1860's scientific experiment with a ballistic pendulum, new methods of design, and improved manufacturing technology permitted the construction of a less dangerous longer range military rocket, capable of protracted storage and with a wide range of military application.

This brief† survey of Konstantinov's work on military rockets will begin with the years 1839, when he was an instructor in the Divisional Fireworks School, and 1840, when he was assistant to the manager of the Laboratory Training Detachment. From 1840 to 1844 he was posted abroad "to gather information on artillery."†† At this period, being familiar with both Russian and Western European literature on artillery and rockets, he began independent research. In 1844 Konstantinov was decorated "for the useful invention of an electric instrument for measuring the velocity of projectiles."

In 1845 he was appointed commanding officer of the "gunpowder, saltpeter, and sulfur division," at the Okhtenskii gunpowder works near Petersburg, where in addition to his teaching duties he continued his research on solid propellants. In 1846-1847, at the Okhtenskii works, Konstantinov took up the design and production of rockets, and also developed a ballistic

* [For an explanation of this and other abbreviations see list on p. 204.]

** In evaluating Konstantinov's work, it should be kept in mind that he did not work alone, but directed an entire staff. The results of the work of all his colleagues, as well as of his own efforts, were published in general reports above the signature of Konstantinov, as head of PRZ, and consequently, in the documents and various historical papers dealing with rocket engineering in Russia at that period, all the accomplishments in the field are regarded as the work of Konstantinov.

† For more detailed accounts, see Sonkin, M.E. Russkaya raketnaya artilleriya (Russian Rocket Artillery), Moskva, 1952; and Khramoi, A.V. Konstantin Ivanovich Konstantinov, Moskva-Leningrad, 1951.

†† From Konstantinov's service record. AIM Archive.

pendulum and an instrument for the stand testing of rockets. In 1848 and 1849, as head of the Okhtenskii percussion cap works, he took charge of rocket production, which went on, parallel to the work of PRZ, in two of the plant's shops.

Some rocket components were manufactured in the Petersburg Arsenal and Technical School, where Konstantinov had already proposed a number of machines (drilling and cutting machines, vibratory mills for crushing the fuel ingredients, etc.) for the improvement of rocket manufacturing technique.

In 1850 Konstantinov was appointed director of the Petersburg Rocket Institute, with which all of his subsequent creative activity was connected. Konstantinov reorganized the factory and mechanized its technique, attaining strict uniformity in the process of rocket manufacture.

His scientific experiments enabled him to increase the range of rockets, improve their accuracy and eliminate weaknesses in the rocket casings.

The instruments constructed by Konstantinov for stand testing of rockets (the ballistic pendulum, chronograph, and others) played a great part in this work. Some of Konstantinov's designs and theories are still of value at the present day.

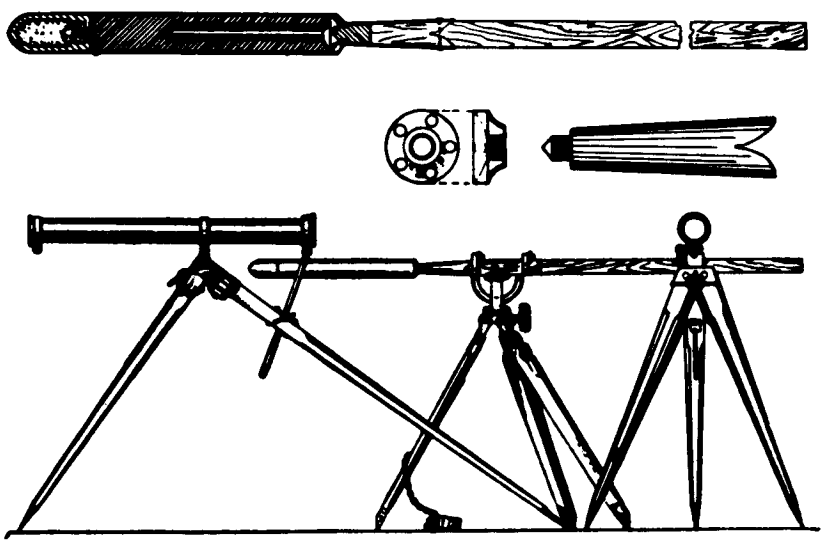

FIGURE 1. Details of one of Konstantinov's 2-inch rockets and general view of a rocket launcher

In 1856 he formulated the law: "During every instant of the combustion of a rocket propellant the momentum imparted to the rocket is equal to the momentum of the escaping gases."*

Konstantinov was the first to consider the eccentricity of reactive force as one of the factors determining the deviation of rockets, and to seek methods for reducing its influence. He correctly explained the effects of wind on the flight of rockets and also proved that rockets are not economical at low velocities (as motors of boats, sledges, or carriages).

* Konstantinov, K.I. O boevykh raketakh (Military Rockets), p.20. Sankt-Petersburg, 1856.

After 1859 a special control for the manufacture and use of rockets existed as part of the Staff of the Master of the Ordnance and Konstantinov was put in charge of it. After studying the use of rockets in foreign armies and evaluating the attainments of Russian designers, Konstantinov worked out design methods for Russian military rockets, establishing directions for their manufacture, and also clearly formulating their basic tactical application.

The appearance of a Russian military rocket in the middle of the nineteenth century is shown in Figure 1. Military rockets of 2", 2.5", 4", and other calibers were manufactured, but the most common was the 2", since it was considered the most successful for action in mountainous terrain, such as the Caucasus.

At that time the manufacture of high quality powder had attained a high level in Russia, which naturally had a favorable effect on the development of military rockets.

Konstantinov and his colleagues developed an improved type of rocket; their other work on the alteration of rocket design included the testing of various solid propellants, as well as experiments with exhaust orifices of various cross sections, length and diameter of the ignition channel (a channel in the middle of the propellant), and means of stabilization.

At that time the design of rocket warheads was systematically modernized in accordance with tactical and technological needs, and assumed spherical, cylindrical ogival and conical forms. Some rockets had heads detachable in flight (by the burning through of their attachments) while others were fitted with nondetachable warheads. Hence the many ways to fasten the warhead to the rocket: i.e., by means of tape, cords, metal bands, rigid elements, and threaded connections or screws which were specially fitted to the warhead. Special protective tubes, whose design was improved by Konstantinov, were used to prevent breakage of the warhead.*

As previously, rockets were stabilized by a central tail. Other methods of stabilization were also proposed: i.e., by the use of fins (the design of Kalinnikov and Vishnyakov) or an arrangement of contiguous planes like a prism. However, neither of these methods proved suitable for military rockets, since they did not give a sufficiently flat trajectory. The suggestions advanced in England, France, and Russia** to employ the rotational motion of the rocket to improve its steadiness in flight and reduce deviation were technical innovations. For this purpose oblique or tangential orifices for the escaping gases were proposed; reinforced spiral or oblique surfaces immersed in the stream of the escaping gases; slanting stabilizers; spiral guides for the launchers; and finally, a thorough prelaunching check. However, in the majority of Russian rockets, rotation was ensured at the expense of part of the reactive force. Due to the relatively weak, black powders then in use, the range of the rocket was substantially reduced and the production of rotating rockets was therefore not then undertaken. Many of these ideas, in the form of finned, cranked, and turbo-jet missiles, for example, have now been realized thanks to the achievements of contemporary technology and the use of new propellants (smokeless powder, liquid fuel, etc.).

The technology of rocket manufacture underwent substantial changes, and special machines came to be more widely used, i.e., cutting lathes,

* Patent No. 26356.

** An instance of the last are the experiments of Lieutenant Berdyugin of the Tiflis Chasseurs Regiment (1855).

riveting machines, new drilling machines, powerful hydraulic presses, designed by Konstantinov and ordered in France, etc. An all-purpose control instrument (for calibers, templates, moulds, inside callipers, guards, etc.) was introduced. Control instruments were required to govern the quantity of powder and the force of compression when compressing solid rocket propellants. Considerations related to construction engineering impelled a change in the form of a crucial component of the rocket — the base plate. Instead of spherical plates whose exhaust orifices had inclined axes, flat plates with orifices parallel to the rocket's axis could be stamped. Seamless (1853), soldered (1855), and welded steel casings (1890)* were all proposed for rockets.

The outcome of three years of experimental studies with 160 different types of rockets during the 1860's was an experimental model with a range of 5.3 km for a 4" bore and 2.6 km for a 2" bore.** On the whole this was due to the use of more powerful dry powders which did not get damp before filling. Four inch rockets could throw a 10 lb projectile 4 km.†

Among Konstantinov's original designs is a two-chamber (double vacuum) rescue rocket which carried a line and achieved the greatest range among rockets of this type.

Konstantinov described this rocket in a report to the staff of the Master of the Ordnance in 1858. By 1859 the rocket had already undergone surface sliding tests, and in tests held in 1862 a 2" double vacuum rocket without a line attained ranges of 1704 meters (with launching angle α of 25°, and head weighing 0.4 kg) and 2130 meters (with $\alpha = 45°$, weight of head 1.1 kg).

In the two chamber-rocket, combustion of the propellant took place more slowly than in a conventional single vacuum rocket. The reactive force acted over a longer period, with a resulting increase in range; furthermore, the rocket flew along a steeper trajectory†† without breaking the extended line.

The 3" double vacuum rocket (with vacuums of 355.6 and 228.6 millimeters) attained the greatest range among Russian rescue rockets carrying a line: for $\alpha = 35°$, it reached 523 meters,‡ which was more than rescue rockets of foreign make. In the patent Konstantinov received for his inventions (No. 26356), attention is called to "a system of rocket construction with two vacuums, which resolves in the most favorable conditions the question of line-throwing and gives a highly auspicious beginning to the realization of long range rockets (author's emphasis — V. T.), rockets for the launching of sliders, and demolition rockets for action on the pipes of countermine systems." Konstantinov's rescue rockets went into production at the Nikolaev Rocket Plant.

His various successes in the development of rocket design and manufacture three times earned him the Mikhailovskii prize, awarded for outstanding achievement in the field of artillery.

* They were not actually produced then, since at that time in Russia there was no industrial production of seamless pipes, and proper welding methods had not yet been established.

** AIM Archive, VUK Folio, entry 40, file 407, sheet 2.

† AIM Archive, ShGF Folio, entry 54/3, file 218, sheet 23.

†† Artilleriiskii Zhurnal, No.5, 1863; Konstantinov, K.I. Spasatel'nye rakety i spasatel'nyi zmei (Rescue Rockets and the Rescue Kite), Nikolaev, 1869.

‡ TsGA VMF, Folio 421, file 6, sheet 104, 1874.

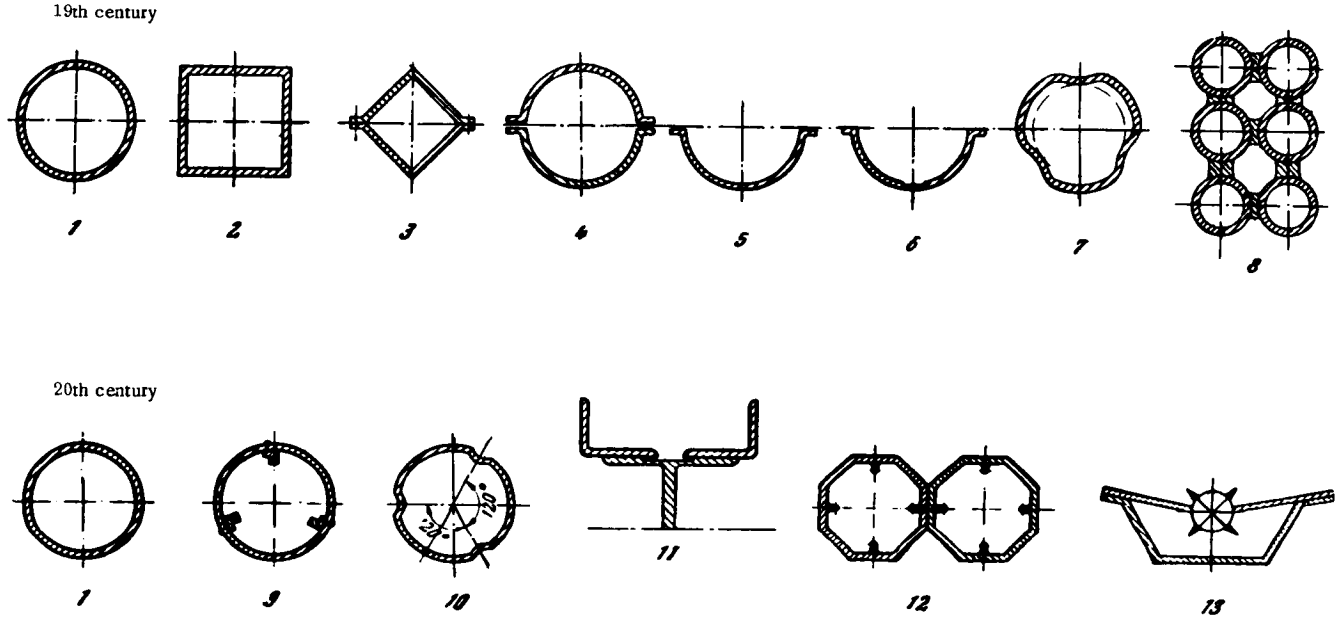

FIGURE 2. Cross-sections of launcher guides, 19th and 20th centuries

1) tubular; 2) square; 3) split square diagonal; 4) split circular; 5) gutter-shaped; 6) gutter-shaped, with slot beneath rocket joint pin; 7) tubular fluted with indentations; 8) honeycomb with six, nine, and fifteen tubes; 9) tubular with angle bars; 10) tubular with indentations; 11) groove guide; 12) honeycomb guide; 13) groove guide

In the second half of the 19th century, Konstantinov, together with V. V. Nechaev, F. V. Pestich, Amel'fin, Bogoslovskii, Raevskii, A. Lazarev, and others, turned to the design of rocket launchers. The weight of the launchers was reduced and their design simplified to permit the shooting of curved fire, grazing fire, and signal lights without changing the guide tubes. These took many forms: circular, square (both whole and with a hinged upper part), fluted with indentations, semicircular with a slot under the joint-pin, and gutter-shaped. Some of the above-mentioned cross sections are used in construction of modern launchers (Figure 2). The tactical applications of rockets then known have retained their importance to the present day: rockets are employed for salvoes and massed fire and used in landing operations; and rocket heads are used by independent military subunits and field engineering units, as well as in the navy.

The high quality of Russian military rockets and their skillful application are attested by the numerous instances of their use in the Caucasus, in the Russo-Turkish War of 1828-1829, and in the Crimean War, 1853-1856. Documents in the archives, the recollections of eyewitnesses, and the war reports of the second half of the last century provide information about the use of rockets in battle.

In 1853, for example, a mounted rocket battery under the command of Lieutenant Andronov successfully deployed in the environs of the town of Babadag, where the rocketeers, in conjunction with a division of the Bug regiment of Uhlans, compelled the Turkish cavalry to retire from the town, and pursued them. In February, 1854, two thousand rockets and twenty-four horse-drawn rocket stands were sent there. The rocketeers also distinguished themselves in the battle of Kyuryuk-Dara, between Russian and Turkish forces, on 24 July, 1854, where a Russian army of 18,000 inflicted defeat on 60,000 Turks.

In August, 1854 a detachment of infantry and cavalry with twenty light guns and eight rocket stands was sent to Kars under the leadership of Kovalevskii. Six detachments of rocket cavalry, and six of infantry, were to be found among the Black Sea Cossacks in 1854. It is known from the war journal of the detachment's Chief of Artillery, Lieutenant-Colonel Kudryavtsev, which covers action in the Caucasus in 1854, that the rocket detachments of the Navaginskii and Tenginskii regiments participated in a number of battles. The total number of rockets among the troops, however, was still too small and they could not therefore be used in quantity to produce salvoes and massed fire. This was a serious shortcoming in the application of military rockets.

Rockets were successfully used in the attack on Ak-Mechet (General Perovskii's expedition), in warding off the assaults, at a number of places, of the Turkestan command, and also at Reval, Bucharest, and in other sectors. In 1855, Russian military rockets were used, in insignificant numbers, it is true, against the British and French in the defense of Sevastopol. All Russia's military garrisons had rockets, and even a few ships were equipped with them. According to the report of Commander Savinich, of the Caucasus Corps, the boats of the Cossack rowing fleet in the Caucasus were equipped with stands for 2" rockets, and the steamships, for 2.5" (12 and 24 pounders).

In 1854, apart from the regular rocket division, a special naval rocket training detachment, attached to PRZ, was formed and placed under

Konstantinov's direction. In 1855 it performed well in firing experiments at Reval, where 4" and 5" rockets were thrown. The Kronstadt rocket detachment was formed subsequently, and others followed.

In 1864 the Zachuiskii detachment used 4" and 2" rockets on the River Chu, in Central Asia. In the years 1868 to 1870 rocket detachments in the Zeravshanskii Command (in Turkestan) performed well in battles for the towns Sharem and Ketab under the general leadership of Major-General Abramov.

Rockets saw military action in Bukhara (1868), and in the Khivinskii campaigns of 1874 to 1881. PRZ sent 1500 rockets to Orenburg, Omsk, and Turkestan in 1871, and 6000 to Turkestan and Krasnovodsk in 1872. Rockets were also used in the Russo-Turkish war of 1877 to 1878, though on a smaller scale than before.

However, in spite of the long-standing and relatively wide use of rockets in the army, by the middle of the nineteenth century their military qualities (close shot grouping and range) were being superseded by rapidly developing rifle artillery. This was in the main due to the lack of exact knowledge in the fields of jet propulsion, ballistics, and rocket aerodynamics. It is therefore not surprising that with the swift development of rifle artillery and the demonstration of its tactical superiority, the use of rockets for military purposes was universally discontinued.

Production of military rockets nevertheless went on longer in Russia than in other countries and was not officially abandoned until 1887. In fact, they were still manufactured after that date for experimental purposes and were even used in a number of military expeditions in Central Asia,* the Far East, etc.

From 1870 to 1910 Russian rocket manufacture took place at the Nikolaev Rocket Plant, which produced military rockets, flares, signal flares, and rescue rockets, and systematically aimed at the improvement of design and manufacturing technology. From 1910 to 1917 rockets were manufactured in workshops of the Shostenskii Gunpowder Plant. In 1872 a military rocket stand, with a rocket, was displayed in the military section of the Polytechnic Exhibition in Moscow, and this is mentioned in the catalogue of the exhibition; but only signal flares were demonstrated at the Nizhegorod exhibition of 1896, and rescue rockets at the Brussels Industrial Exhibition.

Rocket enthusiasts continued to propose original schemes for various types of rockets, and new solutions to the problems of flight stability range, shot grouping, etc. In 1878 the well-known inventor Aleksandr Il'ich Shpakovskii, a technician of the Kronstadt mine workshops, developed some new rocket propellants, and in particular, one for mine transport. Lieutenant Bezobrazov also suggested using rockets as motors for mines, but neither of these two projects was taken up by the army.

Konstantinov's pupil and disciple, Viktor Vasil'evich Nechaev (1822-1906), who succeeded him as head of the Petersburg Rocket Institute, and subsequently at Nikolaev, where the Petersburg plant was transferred, developed special types of compressed charges, "gunpowder rings," for the throwing of mines. Composition of the powder and the weight, form, and density of the charge were determined by experiment and calculation.

* In 1899 rockets were employed in Turkestan (Brockhaus and Efron Encyclopedia, "Rocket", Vol. XXVI, 1899).

Nechaev recommended the construction of pyroxilin rockets, which had been tested successfully at Nikolaev in 1877, and in 1878 on the Volkovskii range, near Petersburg. The Artillery Committee, in its gazette for 14 September, 1877 (No. 389), gives notice of a special decision "about the use of mine rockets with pyroxilin in land artillery," in which it is particularly pointed out that "the explosive effect of pyroxilin exceeds that of a charge of ordinary powder four times its weight." Such rockets were clearly suited to the bombardment of fortresses, and they were used in the Russo-Turkish War of 1877-1878. At Parodima, for example, they were used with effect by Lieutenant Ryumin's rocket detachment, part of the Rushchukskii task force (commanded by Lieutenant Brandt), at Pleven, etc. The military value of these rockets is attested by General Totleben's request that as many pyroxilin throwers as possible be sent to the Army in the Field.

Colonel Zavadovskii devoted himself to experiments on the improvement of flares. After successful tests at the Nikolaev proving ground, his 3" flare was adopted by the army and used not only in the war of 1878-1879, but also in the Civil War (1917-1920).

In 1890 Staff-Captain Andreev proposed a number of improvements to increase the range and accuracy of 2" military rockets and 3" flares. These included, besides development of superior manufacturing techniques, use of more powerful solid propellants; lengthening the casing without increasing its weight, through the use of light metals or alloys; replacement of the wooden stabilizing tail by a metal one (of sheet iron) located inside the channel through which the gases pass. He guaranteed a velocity of 336 meters per second for his design, and accuracy equal to that of the 1867 mining bomb, but the Artillery Committee dismissed the proposal, since use of rockets for military purposes had been discontinued. After 1892* some Russian rocket designs incorporated stabilizing tail fins consisting of three planks arranged as the edges of a right trihedron.

At the beginning of the twentieth century, Colonel Mikhail Mikhailovich Pomortsev (1851-1916), an instructor in the Artillery College, conducted more extensive research into the planning and manufacture of solid-propellant rockets. After 1902 he was particularly concerned with perfecting the design of military rockets and flares, and increasing their flight stability by the use of new types of stabilizers (Figures 3 to 5). The accomplishments of Pomortsev will be discussed in some detail here, since until now little about them has appeared in print. A 1902 memorandum from Pomortsev to GAU reads:

"Over the course of my extended study of aircraft, I have developed a system of surfaces possessing a considerable lifting force and great stability of motion through the air. The adaptation of such surfaces for rockets could make them a highly accurate means for the transportation of explosives and illuminating substances over long distances, and transform them into a sort of aerial torpedo."** Pomortsev's work was highly esteemed by Major-General Zabudskii and Colonel Timkovskii of the Artillery Committee.

In 1902 Pomortsev performed his experiments at Kronstadt and in the Petersburg Gunpowder Laboratory, and from 1906 on he worked with colleagues from the Nikolaev Rocket Plant. By 1905 Pomortsev had developed

* AIM Archive, Artillery Committee Folio, entry 39/3, file 349, sheet 299.

** Ibid.

new types of rockets propelled both by gunpowder gases and compressed air. He worked on the latter type until his death in 1916.

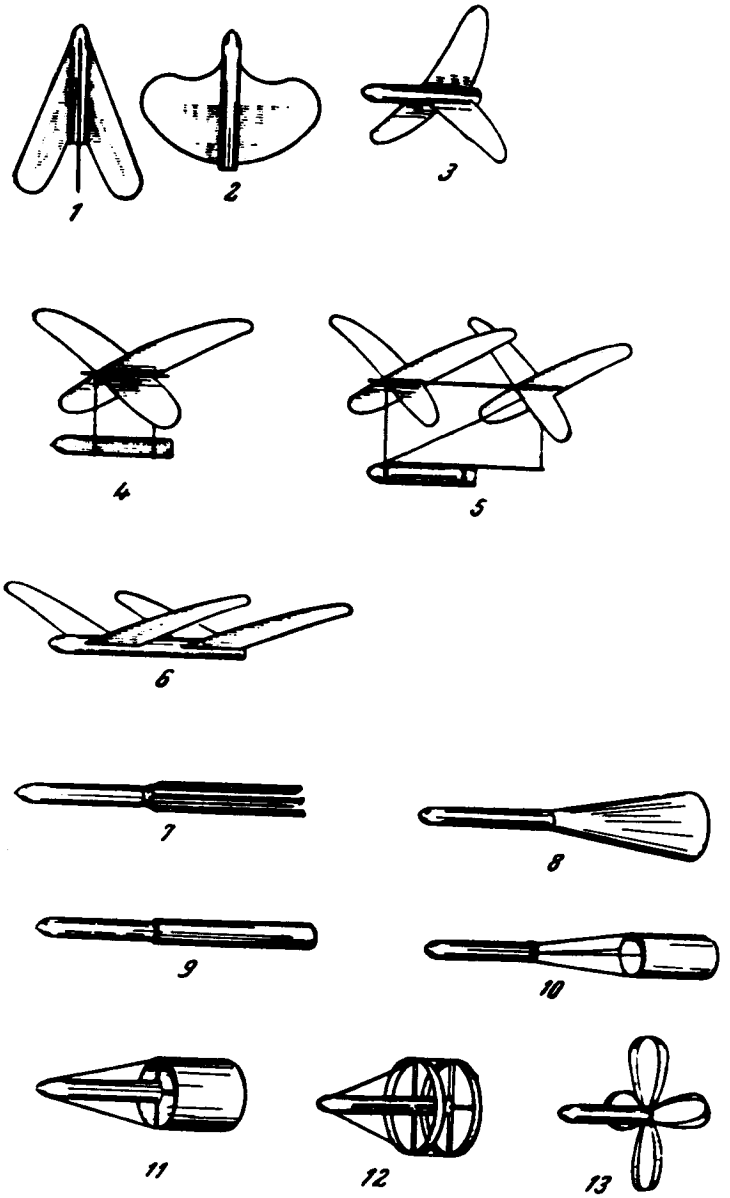

FIGURE 3. Sketches of experimental rocket designs with different types of stabilizers. (Photocopy of Pomortsev's drawings)

Pomortsev's experiments on the use of various types of surfaces as rocket stabilizers yielded interesting results as early as 1902. The object

of his labors was "to study the motion of various types of surfaces, launched into the air with great velocities, and to verify the results obtained by myself and other investigators... so that by their use rockets may be made to follow a more correct flight trajectory." He further wrote: "It is known

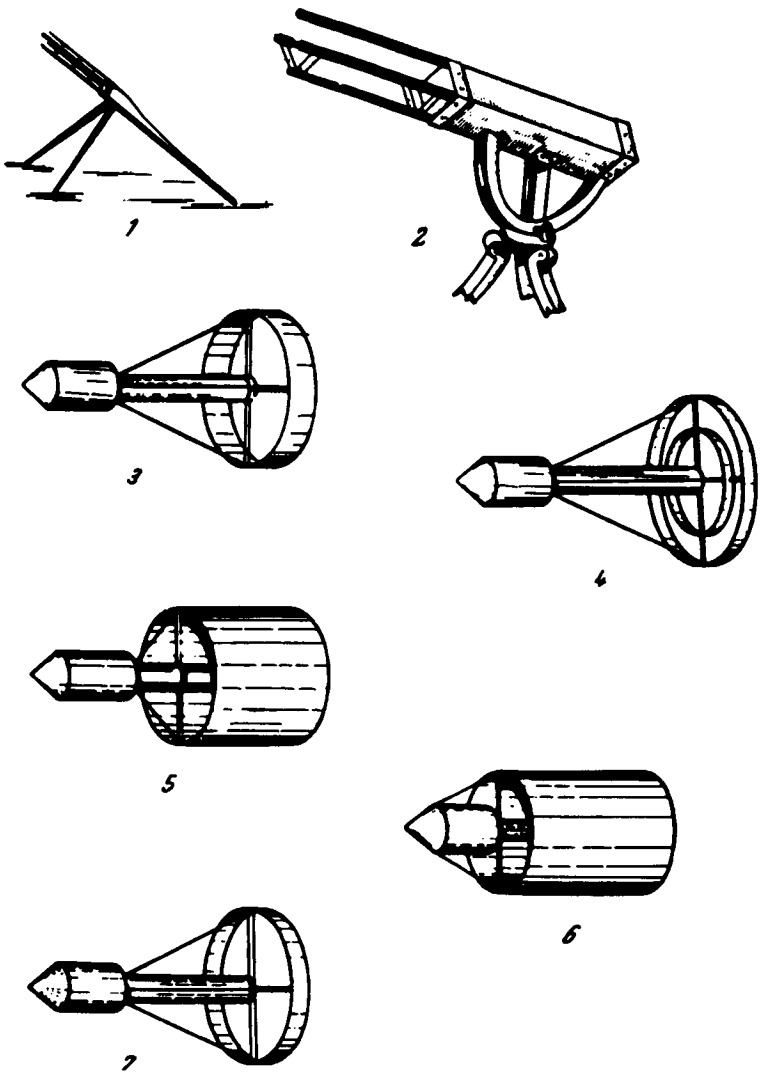

FIGURE 4. Sketches of experimental rocket designs and launching stands. (Photocopy of Pomortsev's drawings)

that in the case of motion of various surfaces at a certain angle to the direction of motion, the center of air resistance* is always nearer to their

* Now called the center of pressure.

rear edge, and for gradual movement in this direction, the angle of inclination is decreased. The center of air resistance, for very small angles, is at a point corresponding to one third of the surface's longitudinal extent from its rear edge. Furthermore, the position of the center of air resistance also depends upon the velocity of the motion, and, all other things being equal, is correspondingly closer to the rear edge for higher velocities. These factors have a great deal to do with the rocket's motion and equilibrium in the air. Until now it was accepted that (a) the force launching the rocket continues to act throughout the duration of its flight, and (b) the center of air resistance is always behind the rocket's center of gravity. It has now been shown that these two propositions are actually far from the truth.*

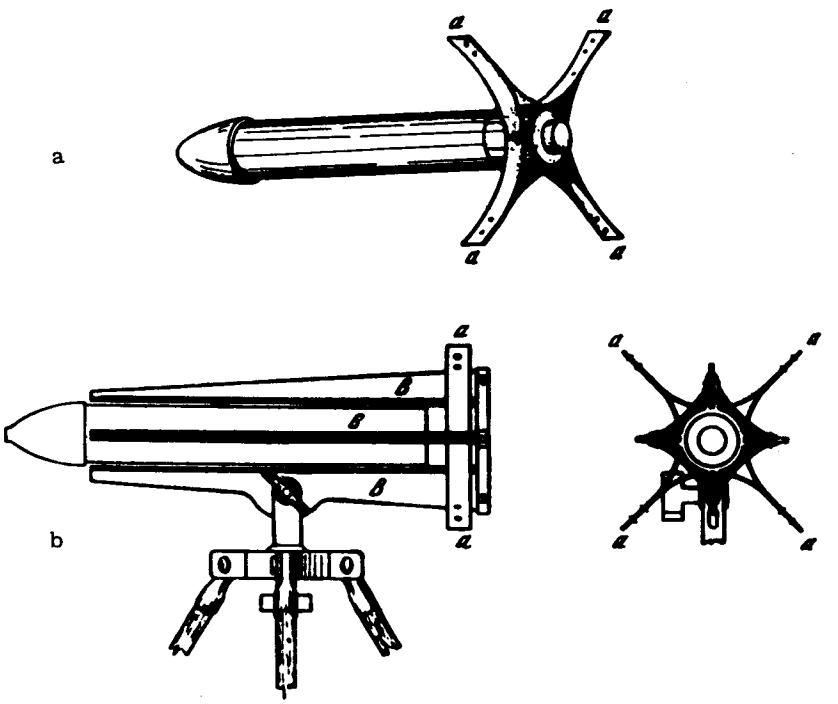

FIGURE 5. A rocket with (a) star-shaped (fin) stabilizer and (b) its launching stand. (Photocopy of Pomortsev's drawings)

Pomortsev studied signal rockets, to which stabilizing surfaces of various forms (Figure 3, 1-6), consisting of a steel framework enclosed by sheets of aluminum or some other durable material, were attached. The stabilizers, single or double (Figure 3, 1-3, 6) were fastened directly to the rockets themselves, or the rockets were suspended from them (Figure 3, 4-5).

For the launching of these rockets Pomortsev constructed a small stand (Figure 4, 1) on which the rocket was seated among four thin directing tubes. The experiments performed showed that it was impossible to obtain a

* AIM Archive, Artillery Committee Folio, entry 39/3, file 349, sheet 372.

correct flight trajectory with stabilizing surfaces whose direction does not coincide with the rocket's axis, since the slightest angle between this plane and the rocket's axis was enough to produce rotation, and send the rocket off course.

The second series of experiments was carried out with tubular stabilizers made of slender aluminum or steel plates (Figure 3, 7) and placed behind the rocket main body (Figure 3, 7-10). These stabilizers gave a correct trajectory but diminished range, since the escaping gases failed to clear the stabilizer and lost velocity through friction.

Experiments with 3" (76.2 mm) flares, performed under Pomortsev's direction, showed:

1) the need to change the form of the rocket head, since its diameter exceeded that of the rocket's body, and gave rise to considerable air resistance;

2) the necessity of new types of stabilizers, since the long wooden-tailed design previously used unnecessarily moved back the rocket's center of gravity, and at the same time, on account of its small moment, contributed little to flight stability; the resulting oscillations consumed a part of the moving energy and increased flight irregularity (diminishing the closeness of grouping);

3) that 3" flares have short range (about 1 km) and deviate from the aiming plane.

As a result of Pomortsev's experiments the range, velocity, and accuracy of both military rockets and 3" flares were increased. In 1905 he summarized his achievements in a memorandum to GAU. At that time rockets with stabilizers of his design attained ranges of 2 to 3 km, and described trajectories as accurate as those of spherical shells shot from a mortar.

Excellent results were obtained by rockets with annular stabilizers consisting of steel or aluminum ribbons, attached to the rocket's tail end and concentric with its body. Such rockets described a straight line trajectory even in a high wind.

After numerous experiments, final official trials of rockets with the new stabilizers were held, with outstanding results: the range of flares was increased from 1000 to 4200 meters, and that of military rockets from 4240 to 7000 meters and more.

By studying the motion of rockets with fin stabilizers, Pomortsev tried to give a theoretical foundation to some of his experimental results. He arrived at the conclusion that the reason for deviation in flight must be sought in the fact that the thrust causing the progressive motion of the rocket (the reactive force) acts only in the first seconds of flight, and the completion of the rocket's journey is due to the force of inertia. (Pomortsev's first assertion is mistaken, since a force acting for a certain time is not termed a thrust, but it is true that the remainder of the flight is due to inertia). In confirmation of his deductions Pomortsev cited the work of Konstantinov (1864), who, studying the motion of a 4" rocket on a ballistic pendulum, concluded that the energy developed by its gases totalled almost 53 ft-lb (250 kg-m), and was completely dissipated in the first 2.5 seconds after ignition (i.e., not instantaneously). In stand tests Pomortsev substantiated Konstantinov's deduction (1856) that the burning of a solid (dense) propellant in a rocket does not increase the propulsive (reactive) force, since the latter is developed only by the burning of the propellant in the channel.

By studying the movement of various stabilizing surfaces in air for aeronautical purposes, Pomortsev tried to find the theoretical relation between the weight of these surfaces and the force necessary to propel them. Designating by F_0 the force required to propel a body horizontally through the air, by V, its initial velocity, by $2K$, a coefficient depending on the shape of the stabilizing surfaces, and by P and g, respectively, the weight of the body and the acceleration due to gravity, he obtained the empirical expression

$$P\left(\frac{V}{g}+\frac{2K}{V}\right)=F_0.$$

It was supposed that the energy developed by the gases in a 3" rocket of the old design did not exceed 150 kg-m.* Such a rocket weighed about 15 kg and in the course of 30 to 40 seconds covered a distance of 600 to 800 meters quite smoothly, with a velocity of about 20 m/sec. The above expression therefore yielded

$$F_0=15\left(\frac{20}{10}+\frac{2K}{20}\right)\simeq 30,$$

that is, the force F_0 required to launch the rocket from rest is equal to about 30 kg (neglecting the small factor $K/10$), or, to put it differently, all the energy of the gases is dissipated in the first seconds of flight. All these facts brought Pomortsev to the correct conclusion that the reactive force acts only during the first moments of flight, and that the remaining motion of the rocket is due to inertia.

In 1903 Pomortsev wrote as follows about the factors contributing to stable rocket flight:

"However well a rocket is made, when it is in motion it is always possible for there to be a certain angle between the axis of the rocket and the direction of motion. For small angles of inclination and considerable velocity, the center of air resistance** is undoubtedly quite close to the nose of the rocket, the appreciable pressure on which also significantly contributes to this factor. As a result of this, the rocket's center of gravity in luminous rockets (located 53 cm from the forward end) will occur behind its center of air resistance and the rocket in motion will be in unstable equilibrium. The disturbance in equilibrium will persist until the rocket's axis makes such an angle with the direction of motion that the center of air resistance moves backward relative to the center of gravity. The resulting air pressure on the rear of the rocket displaces its axis, through inertia, in the opposite direction from the foregoing, etc. The consequence of all this is an oscillatory movement which is always observable in rockets with tails, can mount to 10° and more in the case of luminous rockets, and which, consuming an enormous amount of the rocket's propulsive energy, reduces its range and increases its inaccuracy."† In order to improve the flight stability of both military rockets and solid-fuel flares, therefore, Pomortsev also proposed a new type of stabilizer in the form of rings or cylinders attached to special tie rods and concentric with the body of the rocket. These annular stabilizers were of various lengths and diameters. They were most often made of thin but wide sheets of steel or aluminum, fastened to the rocket by a cross piece of steel wire (Figure 4, 3-7).

* For a 4" rocket, 250 kg-m (according to Konstantinov, 1864).

** See footnote on p. 10.]

† AIM Archive, Artillery Committee Folio, entry 39/3, e.kh. 349, sheet 373.

In the first trials annular stabilizers often broke off in flight, but those rockets which retained them followed a sufficiently true trajectory through the air, i.e., without any deflection, even in the presence of a strong side wind. The experiments showed that the diameter of the stabilizing rings or cylinders had a greater effect than their width on the accuracy of rocket flight.

The other means of stabilization proposed by Pomortsev consisted of bushings made of sheet steel, which were screwed on to the rocket. To them were riveted three or four semicircles of steel ribbon, 50 mm wide and 1 mm thick, which were attached to one another, as shown in Figure 5 ("a-a"). These star-shaped vanes, cutting the wind along their own planes, offered low resistance and served as good rocket stabilizers. Rockets with such a system of stabilization, as experiments on the chief artillery proving ground showed, flew farther and straighter than tailed rockets. These stabilizers could be transported separately from the rockets and attached to them directly before firing.

Pomortsev constructed a light launching stand (weighing about 16 kg) to launch rockets with vane stabilizers. The upper part of the stand consisted of four guide strips B-B (Figure 5), made of sheet iron and arranged in pairs in two mutually perpendicular planes, so that their inner edges were parallel. The rear extremities of the guides were joined by an iron ring and brace strips, but the front ones were free, so that the body of the rocket could fit between them with a small margin. This stand was mounted on a tripod which could easily be set up at any angle to the horizon. The advantages of this stand included its lightness and portability, which made it maneuverable on the battlefield, the more so because its weight could be substantially decreased by the use of light metals. The gases flowed unimpeded out of the rocket and did not interfere with its flight, unlike the case of earlier launching stands, on which the rocket was enclosed in a four sided guide box. The only drawback of such launchers was the shortness of the guides, which affected precision of flight.

In the Artillery Committee Reports of 1906, where Pomortsev's achievements were evaluated, it was noted that luminous rockets of his design (with annular stabilizers) had a range of 3.2 to 4.2 km (3 to 4 versts) with full flight precision, which was a notable achievement for that time. (It was pointed out that earlier luminous rockets with wooden tails had a range of only 1 km and served more "to illuminate the marksman himself than his target.")

Pomortsev also suggested alterations in the technology of rocket manufacture. In particular, he recommended using for the body of the rocket casings drawn from soft steel and weighing 2 kg, which were almost three times as light as the riveted casings of sheet iron manufactured in the Nikolaev Rocket Plant. The new casings could withstand a pressure of 200 to 300 atmospheres, i.e., considerably more than those previously used. The bodies of such rockets would weigh half as much as the earlier ones, would cost less,* and have a considerably greater range. The Artillery Committee decided to adopt Pomortsev's suggestion to redesign existing rockets and develop a new type of military rocket, particularly stipulating that he would also work out designs for incendiary and high explosive rockets, and, in accord with his own advice, reduce in size the warheads

* Some machining operations were no longer required.

of luminous rockets, giving them the same diameter as the rocket casing, so as to improve their aerodynamics.

In 1907 extensive trials of rockets designed by Pomortsev, in which Captain Ennatskii from GAU, Lieutenant-Colonel Karabchevskii from the Nikolaev Rocket Plant, and the plant engineer Demenkov took an active part, were held at Nikolaev and Ochakov. The program of the trials was similar to that of Konstantinov's investigations of fifty years earlier, and consisted primarily of research into the influence of cross-sectional area of the gas exhaust orifices, the dimensions of the rocket vacuum, methods of propellant filling, etc., on the magnitude of the propulsive force. The results of these stand tests are given in Table 1.

TABLE 1

Summary table of stand tests at the Nikolaev Rocket Plant in 1907 (solid-propellant rockets of 3" caliber)

Exhaust, area mm^2	Vacuum diameter mm	Vacuum length mm	Propellant fill pressure abs. atm.	Thrust duration sec	Max. dynamometer pressure, kg
Casing with central exhaust orifice					
4415	25.4	381	40*	1.75	145
954.6	25.4	381	40	1.5	195
503	25.4	381	40	1.5	245
503	19	381	40	1.3	250
284	25.4	381	40		250
503	12.7	381—483	40	2.0	300
Casing with 6 exhaust orifices					
1741	19	381	40	1.75	145
1187	19	381	20	1.25	195
1187	19	381	40	1.5	185
1187	12.7	381	40	2.25	145

* A press pressure of 40 atmospheres corresponds to 3000lb of pressure on the entire cross section of a 3" rocket.

Concurrently with the proving ground firings in Ochakov, rocket propellant combustion studies were in progress in stand tests at the Nikolaev Rocket Plant (NRZ), where research was being done on rocket designs with gas exhausts in the nose. These experiments were terminated, however, since the exhaust orifices were too few and the rocket body burst.

Cruciform and annular stabilizers were tested, with the results shown in Table 2. They were attached to a special bushing, which was screwed to a similar bushing on the body of the rocket. It is interesting to quote Pomortsev's deductions:

"1) The rocket's power is increased by reducing the diameter of the rocket vacuum and increasing its length, but decreasing the area of the orifice cross section (exhaust orifice — V. T.) has less influence. Combustion of solid propellants has almost no effect on the pressure.

"2) Burn out occurs after 1 to 2 seconds.

"3) Rockets with one central exhaust orifice give greater pressure and accuracy than a rocket with a series of smaller lateral orifices.

"4) Rockets with steel guides (annular stabilizers — V. T.) attain considerably greater range, velocity, and accuracy than rockets with wooden tails.

"5) About 75% of the new type of military rockets (3", 3 to 4 kg explosive-bearing warhead — V. T.), keep to the aiming plane. Their range is from 5 to 7 versts (for luminous rockets, 2 to 3 versts)."*

TABLE 2

Summary of experiments with 3" military rockets carrying a conical steel shell, 1907

Exhaust areas mm^2	Vacuum diameter mm	Vacuum length mm	Stabilizer diameter mm	Rocket wt. with shell, kg	Angle of climb, degrees	Range, km
			Annular stabilizer*			
503	25.4	381	203	9.2	40	6.4 along directrix
503	25.4	381	229	8.9	35	6.4 along directrix
503	25.4	381	203	11.4	40	3.2 leftward from launcher
503	25.4	381	216	10.6	35	6.4 along directrix
503	25.4	381	203	11.3	40	4.3 along directrix
503	25.4	381	203	10.1	35	6.4 along directrix
			Cruciform stabilizer (starshaped) **			
284	19	381	203	10.5	33	7.4 along directrix
284	19	381	203	10.5	33	5.3 along directrix
284	25.4	381	203	10.5	35	6.4 rightward from launcher
503	25.4	432	203	11.4	37	7.4 along directrix
503	25.4	432	203	10.4	35	7.4 along directrix
503	25.4	394	203	10.0	35	5.3—6.4 along directrix
503	25.4	394	203	10.3	35	5.3 along directrix
503	25.4	381		8.9	40	4.2—5.3 along directrix
503	25.4	381	222	8.8	35	4.2—5.3 rightward from launcher
503	25.4	381	222	8.8	35	6.4 leftward from launcher
503	25.4	381	267	10.0	35	6.4 rightward from launcher
645	25.4	432	203	11.4	37	5.3—6.4 along directrix
646	25.4	394	203	11.2	37	3.2—4.2 rightward from launcher
1187	25.4	381	311	10.0	45	3.2 along directrix
			Wooden-tailed stabilizer			
1187	25.4	381	—	10.8	45	2.1—3.2
1187	25.4	381	—	10.6	45	2.1—3.2
1187	25.4	381	—	10.6	45	2.1—3.2

* 83% of the rockets rigidly kept to the direction of firing.

** 65% of the rockets rigidly kept to the direction of firing.

To give a general summary of the improvements in solid propellant rockets between 1902 and 1907: signal flares with annular and cruciform stabilizers (Karabchevskii's experiments) attained a range two or three times that of ordinary signal flares. Pomortsev succeeded in increasing the range of luminous rockets to 4 km, and that of military rockets to 8 km.

The experiments also showed that the further development of rockets and launching stands would lead to even better results. However, the

* Rockets of 3" (76.2 mm) caliber are considered. The fully equipped nose of a luminous rocket weighed 7.2 kg. AIM Archive, Artillery Committee Folio, entry 39/3, file 585, sheets 50/71.

closeness of shot grouping was unsatisfactory. The shortness of the guides, above all, was thought to be the cause of this. They would have to be enlarged, particularly in the case of the heavy shells carried by military rockets (3 to 4 kg instead of the 2 kg in earlier rockets). The engineer at the Nikolaev plant, Demenkov, was occupied with the design of improved rocket launching stands.

Pomortsev considered these experiments the foundation of thorough rocket study and felt that they should be uninterruptedly and vigorously pursued. He urged that attention be devoted to the attainment of maximum efficiency in the compression of rocket propellants and to experiment on the use of rotational motion instead of tails or annular stabilizers to improve rocket stability.

In summary, the experiments of 1907 can be said to have laid a thorough foundation for the laboratory (test stand) study of rockets, since some of them were devoted to study of rocket propellant combustion and to determination of the most efficient propellant mixture, the dimensions of the rocket vacuum and exhaust orifices, etc.

Analysis of Table 2 shows that rockets with annular stabilizers achieved the greatest accuracy (83 % strictly held to the line of firing). The longest range was attained by the rockets producing the greatest gas pressure in stand tests, i. e., those with longer vacuums and smaller exhaust orifices.

GAU thought very highly of Pomortsev's work, financed it, and remarked in the Artillery Commission Journal of 28 June, 1908, No. 637, that "Pomortsev's experiments have laid the foundation of scientific rocket research." The Artillery Committee Journal for 3 November, 1903, No. 554, stated that Colonel Pomortsev's new designs included not only an annular stabilizer, but also a compressed air rocket.

The essence of the new rocket design was as follows (Figure 6): a seamless steel pipe *A* with a threaded hole in its head served as a reservoir for air, compressed under a pressure of up to 200 atmospheres. The air-filled pipe was closed by a steel sleeve with head *B*, of diameter slightly greater than the external diameter of the pipe, which was screwed into the hole. Along the axis of the sleeve was drilled a channel whose upper part was threaded. Its smooth middle part, of somewhat smaller diameter, was connected with the lower surface of the head by four mutually perpendicular radial ducts *g*, whose orifices, grouped in perfect symmetry about the axis of the pipe, radiated downward from it. The lower part of the sleeve's central channel, also smooth, and of still smaller diameter, was closed by a brass cup *m*, whose base rested against an ebonite disc *k*. This was clamped to the lower edge of the middle part of the channel by the stem of the central screw *D*, whose head was screwed into its upper, threaded part. In the stem of the central screw below was a recess *f* with a percussion cap. When this was exploded by an electrical spark the ebonite disc and brass cup were broken, permitting the compressed air to escape from the pipe *A* through the radial ducts *g*.

The advantage of placing the exhaust orifices in the rocket head was that the rocket's propulsive force, being applied in front of the center of gravity, contributed to flight stability. The stabilizing vane described above was mounted on the rear end of the rocket, in place of a tail, and a luminous or other projectile *C* was mounted on the nose of the sleeve. Pomortsev showed, from the numerical data given in his notes, that a compressed air rocket weighing 16 to 17 kg, about the weight of a 3" flare, could hold

1.5 cubic meters of air under a pressure of 200 atmospheres. The air, escaping through four radial ducts, each of diameter 2.5 mm, was completely exhausted in 25 seconds, giving the rocket an initial propulsive force of not less than 40 kg, the same as that of a 3" luminous rocket, though its prolonged action gave the compressed air rocket a longer range.

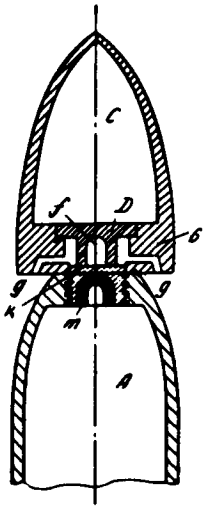

FIGURE 6. Plan of pneumatic rocket designed by M. Pomortsev

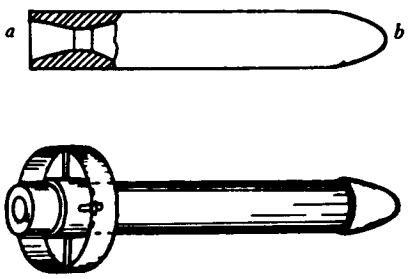

FIGURE 7. Plan of Pomortsev's pneumatic rocket with annular stabilizer

Upon retirement Pomortsev continued his rocket experiments, but since he was dismissed from the direction of GAU, he broke with them and tried to prepare his work for publication. In 1908, however, the Inspector-General of Artillery officially forbade publication of his research as secret.

In 1912, nonetheless, Pomortsev published some of his experiments, together with the sketch of a rocket (known in engineering circles as "the rocket with Pomortsev's stabilizer," Figure 7). He showed that a range of 8 km or more was attained by rockets with this sort of annular stabilizer and an overall weight of 10-12 kg, launched at an angle of 30° to 40° with the horizon.

Pomertsev made the reservation that if the gas stream fails to clear the stabilizer and its extended struts (which can occur if the stabilizer is moved appreciably backward), the resulting reduction in range can be as great as 1 km. The design of the pneumatic rocket illustrated above consisted of a steel pipe, one end of which *b* was blind, with a nozzle at the other end *a*. The nozzle *a*, forerunner of the adjustable nozzle, was closed by a special plug, which could be opened at any moment. In the experiments conducted at Kuchino* this rocket used air compressed at 100 to

* From 1912 to 1916 Pomortsev worked and tested his pneumatic rockets at the private proving ground of Ryabushinskii at Kuchino. Ryabushinskii, who went to France at the time of the revolution, published the results of this work in 1920, after Pomortsev's death.

125 atmospheres, and a charge consisting of gasoline with alcohol or ether, or gunpowder. The launching stands were like those used for conventional solid-propellant rockets.*

The achievements of Pomortsev's administration included the production, between 1903 and 1907, of a new 3" military rocket with steel stabilizers (annular, cruciform, and star-shaped) in place of a wooden tail. The rocket had a warhead carrying 4 kg (instead of 2) of explosive, and a range of almost 8 km. Pomortsev redesigned the nose of luminous rockets to obtain better streamline flow and succeeded in increasing their range to 4 km

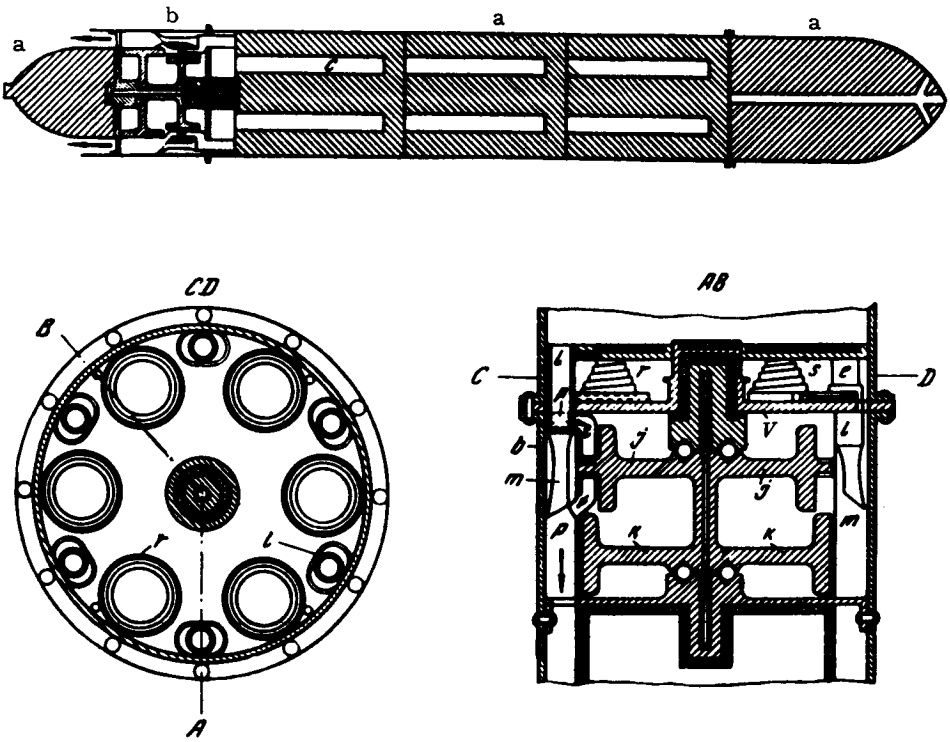

FIGURE 8. Gyroscopic rocket designed by N. Gerasimov

through new means of stabilization. He designed a base plate with a single central** exhaust orifice and nozzle for solid-propellant and pneumatic rockets. His contributions to manufacturing technology included a proposal to use seamless steel casings instead of riveted iron ones.

Pomortsev's research once again graphically underlines the success of

* In D. Ryabushinskii's article, included in the book: Rynin, N.A. "Mezhplanetnye soobshcheniya" (Space Travel), Issue 4, Leningrad, 1929, sketches and charts dealing with Pomortsev's rockets, illustrated in Figure 7, are given.

** Konstantinov described a means of gas exhaust through a central orifice but at that time really durable iron rocket casings could not be produced. It was necessary either to reduce the power of the propellant or to increase the exhaust cross section by using five or six holes.

Russian experiments in the design of solid-propellant and other jet-propelled missiles at the turn of the twentieth century.

In 1909 N. V. Gerasimov, a military engineer, proposed a design new in the history of rocketry, a gyroscopic rocket using an internal gas turbine which was made to rotate by the gases produced by combustion of the propellant (Figure 8).

Gerasimov obtained patent No. 21021 for his design of an engine with compressor and gas turbine (turbo-jet engine, 1909). Gyroscopic rockets were built and tested between 1910 and 1912, both on the chief artillery proving ground and in stand tests at the Okhtenskii gunpowder factory.

Here is Gerasimov's description of the project:

"Having studied rockets in flight, I came to the conclusion that the reasons for their low degree of accuracy were:

"1) The instability of the principal axis during flight; 2) the excessive length of rockets, reaching, with the tail, as much as 25 times the gauge; 3) the shifting of the system's center of gravity as the propellant is burned; 4) the deficiencies in the preparation of rocket propellant, rammed in stages into very long pipes.

"I propose: 1) To stabilize the rocket's principal axis through the combination, within it, of two turbine wheels constituting a gyroscope and rotating with such velocity as to impart to the rocket's axis the axial stability of a shell shot from a gun.

"The turbines are made to rotate by gases produced by combustion of the rocket propellant, and axial stability is achieved before the rocket begins to move along the launcher. After burnout the rotational velocity of the turbines will be maintained by the air entering through the opening in the nose of the rocket and moving with great velocity because of the difference in air pressure between the head and tail of the rocket due to its high speed. The use of a gyroscope always gives stability to the axis of rotation, and there is therefore no question that the rocket axis will remain quite stable. 2) Rockets of my design will have a length of about 6 or 7 times their gauge, in this respect roughly similar to shells. 3) The rocket's center of gravity will always be located in the middle of the space occupied by the propellant, so that the system's center of gravity will not shift after burnout. 4) I propose packing the rocket propellant in fabricated cylindrical casings with an internal vacuum (propellant channels—V. T.), which will be manufactured simultaneously by powerful presses to assure uniformity... Rockets will enable man to rule the heavens from the earth, since rockets can always fly faster and higher than any manned aerial craft."* Gerasimov's rocket consisted of two parts: a cylindrical tube *a*, containing rocket propellant, and another tube *b*, where the two turbine wheels *j* and *K*, seated on a single axle, were located (Figure 8).

Tube *a* was made of 3 mm sheet steel and had an internal diameter of 170 mm. In it were three cylinders *c* of compressed rocket propellant, each containing a cylindrical vacuum, as a result of which the fire was distributed over an area of 1500 cm^2. The cylinders burned consecutively.

Gerasimov remarked that if Konstantinov's observations on the combustion of jet propellant were correct, each cylinder would burn about 2.5 sec. To avoid ignition of the cylinders on the surfaces adjacent to the casing,

* AIM Archive, Artillery Committee Folio, entry 39/3, e. kh. 577, sheet 19.

Gerasimov recommended smearing them with some noncombustible substance,* such as water glass.

Attached to the rivets in tube *b* was a base plate *v*, whose movable bottom *s* had six holes and tubes *e* for the ejection of the combustion products. The movable bottom was maintained in its upper position by the six cylindrical springs *r*, designed in such a way that at a pressure of 2 to 3 atmospheres inside the rocket casing *a*, the bottom began to descend, reaching its lowest position (a journey of 100 mm) at a pressure of 5 atmospheres. Together with *s* the tubes *e* also fell, and the lateral orifices *p* correspondingly began to open for the passage of the combustion products. The gases, except for a small portion first diverted into the ducts of the turbine wheel *j*, passed through them directly into the air.

The area of the orifices was calculated so that the pressure inside the rocket casing would not exceed the limit at which the casing would burst. After burnout air entered the rocket casing through the widening orifice (Figure 8), and all of it passed through the turbine, since the reduction in pressure caused the movable bottom to rise (the lateral orifices would be closed).

The springs and turbine axis were insulated from the hot gases, and a large part of the bottom *s* was therefore covered with asbestos.

In this rocket the first turbine wheel is really the motor of the system; the gases, striking it, set it rotating rapidly, and, leaving it, fall upon the other wheel *k*, constructed like a centrifugal fan. In the first wheel the gases lose part of their velocity, but in the second they acquire velocity and the resultant pressure on the side opposite that of their emission enhances the recoil effect of the gas stream. The upper cover of the rocket body could serve as a base for the explosive warhead, but the explosive could also be placed in the lower chamber behind the turbines, so that it could be distributed in the head and tail parts of the rocket. A pipe was passed through the upper chamber to permit entry of air during flight, and the lower chamber, at its very end, was equipped with a time fuse. The chambers had the form of a body of minimum resistance. This design situated the system's center of gravity in the middle of the propellant, and assured the detonation of both the lower and upper explosive charges by means of the time fuse.

The second variant of this rocket had the gyroscope arrangement at the system's center of gravity. The propellant was divided into two parts, with gunpowder cylinders 13 cm in length, instead of 24 cm, and the displacement of the system's center of gravity during their combustion was less (a maximum of about 17 mm, instead of 28 mm). The only drawback was that some of the recoil effect of the gases was lost, since the gas stream flowing from the forward cylinders had to change its direction. The rocket weighed about 61 kg, of which 13 kg was explosive, 24 kg, propellant, 5 kg, the gyroscope, and the remaining 19 kg, the casing and the other parts. Gerasimov conjectured that the rocket would have a velocity of about 400 m/sec and a range of 8 to 9 versts (about 10 km).

After examining Gerasimov's project, a special GAU conference, presided over by Major-General N. A. Zabudskii, noted:

"Gerasimov's idea, which consists of placing inside the rocket a gyroscope rotating with high angular velocity, is new, and there is a basis for

* Now called burning inhibitor.

thinking. . . , that its use will give better results as regards rocket flight stability and, in general, accuracy of flight, at least on the upward leg."*

By 1910 the rocket had been developed. It was tested twelve times between February and May, 1910 in stand tests at the Okhtenskii gunpowder factory and in trial launchings at the main artillery proving ground. All of the launched rockets, however, burst on the stand** before the gyroscope began to rotate. The design of the rockets was then altered, and the small cylinder of propellant intended to start the gyroscope rotating on the launching stand was placed inside an iron case screwed to the bottom of the rocket, so that all the gases from its combustion passed exlusively into the gyroscope chamber. The large cylinders were ignited through orifices in the cover of the rocket body. Nine such rockets were manufactured, and one was tested at the proving ground. It also failed to leave the stand after burnout, possibly being jammed.

In these experiments Gerasimov's rockets either flew poorly (with very short range), burst,† or flew aimlessly back and forth. The rocket propellant was changed to black powder, which would in any case have been too weak for gyroscopic rockets. In June 1912, four last launchings were held, using a chute, but the range attained was insignificant (520 meters). The commission declared itself dissatisfied.

This was the fate of the first gyroscopic solid-propellant rocket design. It was not realized only because the propellant used (black powder) was too weak for the goals set.

In 1912 Ivan Valentinovich Volovskii, the former vice-president of the Putilovskii Plant, proposed a new type of gyroscopic military rocket, intended to carry explosive missiles. The launchers, rocket batteries with up to 50 guides, would be mounted on automobiles and fired while moving at full speed, and "machine-gun" launchers with 20 guides would be mounted on airplanes.

Ignition was by an electric spark, with controlled firing. The essential details are as follows: the gas products formed by combustion of the propellant flowed out of the rocket by two paths. Some of the gases passed through the hollow stabilizing tail of the rocket and gave rise to a gradual motion. The remainder fell to the external annulus of the stabilizer, from where they passed into four ducts forming planes whose ends were bent at a specific angle to the rocket's axis. There, meeting a series of immobile deflecting planes inclined in the opposite direction, they were made to rotate and their motion, together with that of the remaining gases, propelled the rocket forward.

Volovskii's launcher or "rocket gun" had a control instrument which signalled when connection was made between the contacts in the rocket head and those on the guide. The rockets were seated on the "gun" within square guides, which had on their forward inner surface two contacts, joined by an element located in the space between "guns" mounted on a single axis. Every "gun" had its element in the full network of wires uniting each rocket with the corresponding button on the control instrument, which was located on the gun itself.

* AIM Archive, Artillery Committee Folio, entry 39/3, file 577, sheet 35.

** A launching stand from a 3" linear mortar was used.

† See the reminiscences of A.N. Krylov, Acad. Sci. USSR, where these unsuccessful experiments are described.

The control instrument had a contact for each rocket, and was the rocket battery command's chief means of directing fire. At the moment of loading the gun, the contacts on the rocket head were connected with those on the guide and at the same moment the corresponding buttons on the control device were depressed. The union of the contacts was indicated on the control panel by the illumination of the buttons.

After each firing the rocket contact was broken, and the light corresponding to it extinguished, thereby giving the commander a precise indication of how many rockets were ready for firing.

A folding board, which descended against the plane of the "gun's" muzzle at the moment of its loading, permitted precise alignment of the contacts. The same board, folded over to the other side, and pressed against the opposite muzzle, the so-called breech end of the "gun", served as a blind end for the guides at the moment of firing.

The rocket "machine gun" was intended to fire rockets from airplanes. It did not require a gun-carriage, but had to be of such dimensions and weight as to be portable. Volovskii stated that in the absence of precedents for such a missile, he had developed his "machine gun" completely theoretically.

After consideration of his projects, the Artillery Committee decided:

"In view of the recent interest in discovering improved types of rocket, the Committee sees its way to meeting the inventor halfway and giving him an opportunity to realize his designs in the form of experiments."* Volovskii was granted 1000 rubles for experimentation, and twenty rockets for testing on the chief artillery proving ground were ordered at the Okhtenskii gunpowder factory, but the documents dealing with the results of his work are still missing.

After 1913 Vladimir Andreevich Artem'ev, then working in Brest-Litovsk, was occupied with the design of 3" flares. In 1915 and 1916 he succeeded in modernizing the equipment-bearing part of rocket warheads, thereby making it possible to increase the illumination time of a single rocket from 15 seconds to 1.5 minutes.

To conclude, the years 1900 to 1917 saw a good deal of Russian research on solid-propellant rockets, and a number of original designs. Scientific experiments such as Pomortsev's led to the production of tactically and technically advanced military rockets, but the lack, after 1910, of a special experimental factory for rocket manufacture impeded these activities. The result of casual rocket production in various private plants was a reduction in quality and a considerable increase of the time required for manufacture and the cost of the finished product. This explains the attempts to get some rocket parts, such as parts of Pomortsev's pneumatic rocket and special gunpowder charges for Gerasimov's rockets, manufactured abroad. The War Department did not carry through the projects which it had originally financed, such as Pomortsev's. It was only thanks to the great enthusiasm of their inventors that the original research on solid-propellant and pneumatic rockets partially described above saw the light.

* AIM Archive, Artillery Committee Folio, entry 39/3 file 704, sheet 243.

N66 37128

V. N. Sokol'skii

THE WORK OF RUSSIAN SCIENTISTS ON THE FOUNDING OF A THEORY OF INTERPLANETARY FLIGHT

(Raboty otechestvennykh uchenykh po sozdaniyu osnov teorii mezhplanetnykh soobshchenii)

We are witnesses of today's great successes in the conquest of outer space. The attainments of the past few years have surpassed all expectations, and up to the present day mankind has not ceased to marvel at the exceptionally rapid pace with which space exploration has developed. However, although the first practical successes were obtained literally within the past few years — not seven years have passed since the first artificial satellite left the earth — the history of man's struggle to subjugate the cosmos is very long.

Man has striven to gain knowledge of other worlds for many centuries. For a very long time, however, this interest had an abstract and speculative character and found expression in the most fantastic projects. Only in the last century and a half, in conjunction with the development of engineering, did sounder projects, such as extra-long-range artillery, curved railway track, a giant sling and others, begin to appear; however, none of these projects could be realized in practice. The one real route to the solution of this problem was found only at the end of the 19th century — through the use of aircraft built on a jet principle.

At that time jet aircraft did not seem anything new or unknown. It is curious that the inventors of various countries thought of creating jet aircraft before the problem of flight had been resolved, and before either lighter-than-air or heavier-than-air controlled aircraft had been designed. They were attracted by the apparent simplicity of a solution of the flight problem through engines operating on a jet principle. At the same time, however, the originators of most of the projects limited themselves to producing plans of the engine, giving neither the details of its construction nor the precise amount of energy needed for actual flight.

An analysis of the development of rocket research shows that all 19th century jet aircraft schemes can be divided into three groups, depending upon the means of obtaining the lifting force. (In every case horizontal motion was attained through the reaction of ejected particles of matter.)

In the first group, which followed an aerostatic principle, the jet craft were lighter-than-air, and the lifting force was obtained through a gas lighter than air.

In the second group, which used an aerodynamic principle, the jet craft were heavier-than-air, and the lifting force was supplied by the flow of air about supporting surfaces (wings).

In the third group, which used a rocket dynamical principle, the jet craft were heavier-than-air, and the lifting force was due to the reaction of the ejected particles.

The principal difference between the craft of the second and third groups was that the former required the atmosphere as a kind of supporting medium, while for the latter, it was not only unnecessary, but harmful, since it created more resistance.

The craft of the first group — jet aerostats — offered no prospects and did not enjoy an extended development. The development of the second group led to the founding of jet aviation, and of the third, to the construction of long-range rockets.

TABLE 1

Classification of jet aircraft proposed in Russia in the 19th century

Aircraft group	Source of energy				
	Combustion products			Compressed air or other gas	Water or alcohol vapor
	Monopropellant	Liquid fuel, oxidized by atmospheric oxygen	Liquid fuel, liquid oxidizer		
Lighter-than-air craft (jet aerostats)	Treteskii (1849) Treteskii (1870)	Lebedev (1892)	—	Treteskii (1849) Sokovnin (1866) Nezhdanovskii (1882)	Treteskii (1849)
Heavier-than-air craft (jet airplanes)	Ewald (1886)	Teleshev (1867) Nezhdanovskii (1889)	—	Nezhdanovskii (1882)	Nezhdanovskii (1884) Geshvend (1887)
Heavier-than-air craft (rocket aircraft)	Nezhdanovskii (1880) Kibal'chich (1881)	—	Nezhdanovskii (1882-1884)	Nezhdanovskii (1882) Fedorov (1896)	Geshvend (1887)

Note. In a number of cases the authors of the proposals did not give the design of the aircraft, but limited themselves to setting forth the working principle of the engine (Nezhdanovskii, Lebedev).

The projects of Nemirovskii and Spitsyn are not included in the table, since there are insufficient data on the working principle and construction of the craft they suggested.

An examination of the development of rocket research in Russia shows that in the second half of the nineteenth century over twenty jet aircraft projects, belonging to all three groups, were proposed (Table 1). Throughout this period efforts were repeatedly made to solve the problem of flight by means of jet engines. At first the inventors limited their schemes to the installation of jet engines in lighter-than-air machines (Treteskii, Sokovnin), but subsequently plans for heavier-than-air jet aircraft, based on an aerodynamic principle (Teleshev, Nezhdanovskii, Ewald, Geshvend), as well as on a rocket dynamical principle (Kibal'chich, Nezhdanovskii, Geshvend, Fedorov), began to appear more often.

It is also interesting to break down the projects put forward according to the source of energy. Compressed air or another gas, water or alcohol

vapor, and combustion products, which in turn can be divided into three subgroups, were proposed as sources.

From the point of view of fuel, the idea of S. S. Nezhdanovskii, who in the first half of the 1880's presented a plan for a liquid-fuel rocket engine running on a bipropellant,* is of considerable interest. Liquid hydrocarbons (kerosene) and picric acid had to serve as fuel, with nitric acid or oxides of nitrogen as oxidizer.

The noted physicist P. N. Lebedev also applied himself to the questions of jet flight, and in 1892 presented the fundamental plan of a jet aircraft engine, with a sample calculation of the amount of fuel required.**

Of the groups of jet aircraft considered above, the third is of most interest, since the craft belonging to it had no need of the atmosphere as a supporting medium, and could be used for flights in outer space.

In all of the above-mentioned projects, however, the use of the jet principle was considered only for flights within the limits of the earth's atmosphere. Not one of the authors of these schemes, among whom were Kibal'chich, Nezhdanovskii, Geshvend, and Fedorov, whose craft had no need of the atmosphere as supporting medium, brought up the possibility of using their jet craft for interplanetary flights.

The next stage in the development of rocketry, characterized by the establishment of a theory of interplanetary flight, is inseparably connected with the name of one of the most prominent of Soviet scientists, the founder of rocket dynamics and astronautics, Konstantin Eduardovich Tsiolkovskii (1857-1935).

Thoughts of the possibility of conquering space came to Tsiolkovskii very early— when he was only 16 years old. At that time he suggested using the properties of centrifugal force to attain cosmic velocities.

At the same period he became convinced that his idea was erroneous, but ten years later— in 1883— Tsiolkovskii came to the correct conclusion that the principle of jet propulsion could be used for flight in outer space. In his manuscript work "Svobodnoe prostranstvo" (Free Space)† he showed that the only possible means of movement in space, where no forces of gravity or resistance are operative, must be based on the reaction of particles of matter ejected from the given body, and drew the conclusion that in free space, motion is impossible without loss of matter.

Tsiolkovskii's ideas about interplanetary flight were further developed in his science-fiction works "Na lune" (On the Moon) (1893) and "Grezy o Zemle i nebe" (Dreams of Earth and Heaven) (1895). In the latter, in particular, he first expressed the idea of creating an artifical earth satellite. Tsiolkovskii wrote that "an imaginary earth satellite, like the moon, but brought arbitrarily closer to our planet, to a point barely outside the limits of its atmosphere, that is, about 300 versts from its surface, constitutes, if its mass is very small, an example of a gravity-free environment."†† He also asked "how to impart to an earthly body the velocity

* S.S. Nezhdanovskii's records are preserved at the present day in N.E. Zhukovskii's Science Memorial Museum. See the Science Archive of the museum, No. 2990/1, p.145.

** Journal of P.N. Lebedev for the period from 3 January, 1891, to 22 December, 1911. Archive of the Academy of Sciences of the USSR, Folio 293, entry 1, No. 90, pp. 176-182.

† First published in 1954. See Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol. II, p.25, Moskva. 1954.

†† Tsiolkovskii, K.I. "Grezy o Zemle i nebe i effekty vsemirnogo tyagoteniya" (Dreams of Earth and Heaven and the Effects of Universal Gravity), pp. 49-50, Moskva. 1895.

needed to create enough centrifugal force to overcome gravity, when that velocity must be as high as 8 versts per second." *

Beginning in 1896, Tsiolkovskii undertook more profound theoretical studies towards resolution of the problems of interplanetary flight by means of rockets. This thought was not new; it had been expressed before, but Tsiolkovskii's merit lay in establishing with scientific rigor the possibility of applying the principle of jet propulsion to space flight, and in founding a theory of straight rocket flight.

This problem was complicated by the fact that since rockets were bodies of variable mass, they could not be treated according to the formulas of classical mechanics, founded on Newton's three laws. It was necessary to found a new division of theoretical mechanics — the mechanics of bodies of variable mass.

A major role in the resolution of this problem was played by I. V. Meshcherskii, who published his fundamental papers, dedicated to the mechanics of bodies of variable mass, between 1897 and 1904. In his master's dissertation "Dinamika tochki peremennoi massy" (The Dynamics of a Point of Variable Mass, 1897), Meshcherskii deduced the fundamental equation of motion of a point of variable mass for the first time in scientific literature. In this paper he took vertical rocket climb as an example, obtaining the equation

$$m\frac{d^2x}{dt^2} = -mg + p - \frac{dm}{dt}W - R(\dot{x}),$$

where m is the mass of the rocket; g, the acceleration due to gravity; p, the gas pressure; W, the relative velocity of the burning particles at the moment of their ejection; $\dot{x}$, the velocity of the rocket; and $R(x)$, the air resistance. The x-axis is directed along the ascending vertical.

In view of the fact that at the end of the 19th century rockets had practically no serious use (at that time they were losing their military importance, and designers were making their first tentative and still unsuccessful efforts at using rockets to solve the problems of aviation and aeronautics), Meshcherskii limited himself to setting up the problem of rocket motion in its most general form.

Tsiolkovskii worked out what was for his time the most complete theory of rocket motion with a calculation of the mass change. As early as 1897 he deduced his now well-known formula, establishing the analytical relation between the rocket velocity, the exhaust velocity of the gas particles, the mass of the rocket, and the mass of the charge consumed:

$$V = V_1 \ln\left(1 + \frac{M_2}{M_1}\right),$$

where V is the velocity of the rocket; V_1, the relative exhaust velocity of the gas particles; M_1, the mass of the rocket without explosive charge; and M_2, the mass of the charge.

It is evident from Tsiolkovskii's formula that the velocity of a rocket in free space is theoretically unlimited and depends only upon the exhaust velocity of the gas particles and the relation between the mass of the charge and the mass of the rocket.

This result was of very great significance for the subsequent development of rocketry, since it indicated the possibility of attaining escape velocity

* Ibid., p.50.

and showed the direction that subsequent investigations had to take. Tsiolkovskii's formula showed that to increase the velocity of rockets, exhaust velocity of the gas particles had to be increased and the relative (not the absolute) fuel supply enlarged.

This formula gave the rocket's ideal velocity, without taking into account losses due to the force of gravity and resistance of the medium. Subsequently Tsiolkovskii made the problem more complicated by considering the attraction of the earth and air resistance, and carried out calculations for circumstances close to actual conditions.

In 1903 Tsiolkovskii published his classic paper, "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Space with Jet Machines), in which for the first time the possibility of using rockets for space flight was scientifically substantiated, and the fundamental working formulas of flight given. In this paper rocket engines and their working source of energy were also given detailed consideration. This question is of the greatest importance, since the successful performance of an engine depends to a great degree upon the choice of the most suitable fuel. Because of this Tsiolkovskii devoted a good deal of attention to this matter from the very beginning of his research.

Up to the end of the 19th century only jet engines running on solid fuel—solid-propellant rockets—were in use. Tsiolkovskii showed, however, that the most efficient engine for long-range rockets was one running on liquid propellant (fuel and oxidizer), and gave the fundamental plan of such an engine.

The significance of "Issledovanie mirovykh prostranstv reaktivnymi priborami" cannot be overestimated. Tsiolkovskii deserves special credit for making a substantial contribution to the new branch of mechanics, the mechanics of bodies of variable mass, for founding a theory of rocket flight and calculating the change in mass taking place during motion, and for demonstrating with scientific rigor the possibility of attaining escape velocity.

During the first decade of the 20th century, however, this paper went unnoticed both in Russia and abroad. It was printed a second time (and widely disseminated) in 1911-1912 in the magazine "Vestnik vozdukhoplavaniya" and this was the beginning of the popularization of Tsiolkovskii's ideas of interplanetary flight. In this article he discussed air resistance in detail, coming to the conclusion that the work needed to overcome air resistance constituted only an insignificant part of the effort required to overcome the force of gravity.

Tsiolkovskii did not stop at working out the theoretical problems of jet flight, but gave a number of practical directives dealing with the design and manufacture of separate rocket parts. Between 1903 and 1917 he suggested several designs for spaceships, examining such questions as the control of rockets in outer space, cooling of the combustion chamber walls with one of the fuel components, using high-melting elements, etc.

Tsiolkovskii's ideas were far ahead of his time. At the beginning of the 20th century neither the engineering nor the economic prerequisites for the building of long-range rockets existed. For the realization of his conceptions a series of complex problems related to rocket construction and involving the most varied spheres of science and technology had to be resolved; extensive and protracted theoretical and experimental work was required. Tsiolkovskii's research on rockets was still further complicated by the indifference and skepticism he had to encounter in pre-revolutionary Russia.

Many considered him a dreamer with his head in the clouds and took a skeptical view of the self-taught scientist without a degree. Without either material or moral support, Tsiolkovskii was left to himself. He wrote bitterly, "It is hard to work alone for many years, in unfavorable conditions, without seeing a ray of encouragement or assistance from any quarter."*

Several other scientists and inventors in pre-revolutionary Russia, besides Tsiolkovskii, worked on the problem of jet propulsion, and Fridrikh Arturovich Tsander (1887-1933) must be placed in their first rank.

Tsander began his research on interplanetary flight in 1908, when he performed his first calculations on gas flow from vessels, on the task of overcoming the earth's attraction, and on several other matters connected with astronautics.** In the same year Tsander made his first notations in a special notebook reserved for computations dealing with spaceships,*** and in 1909 he was the first to express the desirability of using the solid structural material of rockets as fuel.†

Between 1909 and 1911 Tsander performed calculations related to jet engines, and worked on the problem of high altitude climb,†† and in 1917 he embarked on systematic deep study of interplanetary flight,††† to which he dedicated his entire life. Among the Russians concerned with the problem of flight in cosmic space Yurii Vasil'evich Kondratyuk (1897-1942), who by his own testimony began his research on interplanetary flight in 1916, must also be included.‡ It was evidently soon after the revolution of February, 1917, that he finished the first verion of his manuscript "Zavoevanie mezhplanetnykh prostranstv"‡‡ in which he considered such questions as the design of a spaceship, the conditions for flight to the limits of the solar system, the creation of intermediate interplanetary bases, the atmosphere's influence on the flight of spacecraft, the use of solar energy, etc.‡‡‡

* Tsiolkovskii, K. "Issledovanie mirovykh prostranstv reaktivnymi priborami" (supplement to Parts I and II of the paper of the same name), p.7. Kaluga. 1914.

** Information about Tsander's work at this period is taken from his autobiography, published in: Rynin, N.A. "Rakety i dvigateli pryamoi reaktsii" (Rockets and Ramjet Engines), p.190. Leningrad. 1929.

*** This notebook, entitled "Die Weltschiffe (Atherschiffe) die den Verkehr zwischen den Sternen ermöglichen sollen. Die Bewegung im Weltenraum," was kept in Tsander's personal archive.

† See on this, Tsander, F.A. "Problemy poleta pri pomoshchi reaktivnykh apparatov" (Problems of Flight by Jet Propulsion), p.71. Moskva. 1932.

†† Tsander, F.A. "Polety na drugie planety i na Lunu" (Flights to Other Planets and to the Moon), p.5. The manuscript is preserved in Tsander's personal archive.

††† Tsander's autobiography, 12 March, 1927. Tsander archive.

‡ Kondratyuk, Yu. "Zavoevanie mezhplanetnykh prostranstv" (The Conquest of Interplanetary Space), p.5. Novosibirsk. 1929.

‡‡ The author handed this manuscript over to B.N. Vorob'ev, the noted historian of aviation, in 1938. In submitting the manuscript Kondratyuk dated it 1916, but a notation at the end of the text testifies to its not having been begun before February 1917. The exact date of the manuscript's composition is therefore subject to more precise definition. Subsequently Kondratyuk revised it several times. Four versions of it dated respectively 1916, 1918-1919, 1920-1924, and 1925, presently exist.

The dates of the second and third versions, too, were only stated by Kondratyuk in 1938, when he consigned the manuscripts to Vorob'ev and are therefore also subject to more accurate specification. The fourth version was edited in 1927 by V.P. Vetchinkin and formed the basis of Kondratyuk's book "Zavoevanie mezhplanetnykh prostranstv", published in 1929. Kondratyuk's manuscripts on interplanetary communications are now preserved in the Institute for the History of Natural Science and Engineering, Academy of Sciences of the USSR.

‡‡‡ It must be pointed out, however, that this and the following versions of Kondratyuk's manuscript were not published in his time. It was not until almost ten years later that they came to be known. They could therefore have no influence whatsoever on the development of rocketry up to the middle of the 1920's, and are of historical interest only. Kondratyuk's paper was first published in 1929.

At the beginning of the twenties, under the influence of the work of Tsiolkovskii, Goddard, Oberth, and Tsander, the ideas of interplanetary communications began to be more widely disseminated in the USSR and were reflected in the pages of periodicals. In 1924 the first Society for the Study of Interplanetary Flight was founded in the USSR. All these facilitated the intensification of research in the field.

As noted above, the problem of attaining escape velocity with rockets had been solved theoretically by Tsiolkovskii by the end of the last century. The technical solution of the problem, however, posed great difficulties. One of the most complex problems was that of designing a rocket that could accommodate the necessary fuel supply, since calculations showed that the supply had to be many times greater than the weight of the dry rocket (rocket without fuel). For example, for a flight to Mars with the propellants then known, the fuel supply would have to be several hundred times the weight of the dry rocket, and for a flight to Mars and return to the earth, the supply would have to be many thousands of times as great as the rocket's dry weight.

The construction of a rocket with such a mass-fuel ratio and design is an insurmountable problem even for modern engineering, and the problem was still more complicated during the first two decades of the century. Soviet scientists, trying to solve this problem, and seeking to establish the theoretical foundations of interplanetary flight advanced a number of interesting suggestions, many of which are still significant at the present day.

Analysis of Tsiolkovskii's formula shows that the most efficient means of increasing the velocity of a rocket is to increase the exhaust velocity of the combustion products. In fact, it is easy to see that if all other things are equal, the rocket's velocity is directly proportional to the relative exhaust velocity of the gas particles. From the very first days, therefore, the efforts of scientists were directed towards finding more caloric fuels, possessing the greatest calorific power.

As early as 1903, taking just such considerations as his starting point, Tsiolkovskii proposed to use liquid oxygen and hydrogen as rocket propellant components. By doing so he obtained a theoretical or ideal exhaust velocity of 5700 m/sec. In justifying this choice, he wrote "I do not know a single group of substances which through their chemical combination would impart such an enormous quantity of energy to each unit of mass of the end product."*

It soon became apparent, however, that there were other fuels with greater calorific power than the combination of oxygen and hydrogen. In 1909 Tsander first had the idea that metals with high calorific power could be used as fuel,** yielding a theoretical exhaust velocity of as much as 6750 m/sec for an appropriate choice of fuel components. Subsequently Tsander returned repeatedly to this idea, continuing to develop and perfect it. Later Kondratyuk also wrote about the possibility of using high-calorific metallic fuel in rockets.†

This path, however, did not lead to a full resolution of the problem. Calculations show that rockets running on chemical fuel cannot (for the

* Tsiolkovskii, K. "Issledovanie mirovykh prostvanstv reaktivnymi priborami" (The Investigation of Space with Jet Machines)

** See footnote † on p. 29.

† Kondratyuk, Yu. "Zavoevanie mezhplanetnykh prostranstv " (The Conquest of Interplanetary Space), pp. 13-18, Novosibirsk. 1929.

relationship presently feasible between the masses of propellant and structure) attain even circular velocity, let alone that required for flight to other planets or for return to the earth. Some other form of energy, considerably surpassing that of chemical fuel, had to be found.

In this case the first step was taken by Tsiolkovskii, who in 1912 expressed the thought that it might be possible to use the energy of atomic decay. "It is thought that radium, continually decaying into more elementary matter," he wrote in 1912, "emits particles of various masses, moving with an inconceivable velocity, nearly that of light... Therefore, if it were possible to speed up sufficiently the decomposition of radium or other radioactive bodies, which probably means all bodies, its use, all other things being equal, could give a jet craft such velocity as to permit it to reach the nearest sun (star) in 10 to 40 years."*

At the same time he advanced the idea of building an electrojet engine, pointing out that 'perhaps with the use of electricity it will in the course of time become possible to impart great velocity to the particles ejected by the jet."**

Tsiolkovskii subsequently returned several times to the idea of building nuclear and electrojet engines. In September, 1925, he wrote, "If on the journey we store up latent (potential) electrical energy or special, rapidly disintegrating radioactive materials, we have means of obtaining great velocity."†

This idea was reflected in his manuscript work "Kosmicheskii korabl'" (The Spaceship). Considering the possibility of using the energy of radium for interplanetary flights, and arriving at the conclusion that, for a variety of reasons, radium could not be employed for that purpose Tsiolkovskii wrote: "But it is possible to use negative (β) and positive (α) electrons, i.e., cathode and anode (or channel) rays; in particular the latter (whose minimum velocity is several hundred kilometers per second), if their velocity can be reduced by a large factor (for example, 100). I am speaking of the use of electricity, whose action is always accompanied by the emission of helium nuclei and electrons."††

Tsander also considered the possibility of using the cathode ray pressure for interplanetary flight, and in the table of contents of his book "Perelety na drugie planety. Pervyi shag v neob'yatnoe mirovoe prostranstvo (Teoriya mezhplanetnykh soobshchenii)" (Flights to Other Planets. The First Step into Unbounded Cosmic Space (The Theory of Interplanetary Flight)) envisaged the following section: "The use of instruments to convert solar rays into low-velocity cathode rays:

"a) flights by the pressure of cathode rays emitted by the spaceship itself;

"b) flights by the pressure of cathode rays which reach the spaceship as a bundle of parallel rays from outside."‡

Kondratyuk also pondered the possibility of using other forms of energy, and as early as the first version of his manuscript indicated the

* Tsiolkovskii, K. "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Space by Jet Machines). — Vestnik Vozdukhoplavaniya, No. 9, pp. 7, 8. 1912.

** Ibid., p. 8.

† Archive of the Academy of Sciences of the USSR, Folio 555, entry 2, file 44, sheet 47, obverse.

†† Ibid., entry 1, file 46, sheet 10.

‡ Tsander, F.A. "Problema poleta pri pomoshchi reaktivnykh apparatov. Mezhplanetnye polety", (The Problem of Flight by Jet Propulsion. Interplanetary Flights), p. 447, Moskva. 1961.

possibility of obtaining reactive force from the high-speed ejection of such material particles as cathode rays, α and β particles, etc.*

It is evident that the velocity of these material particles exceeded by many times that of the combustion products of chemical fuels. The use of these forms of energy would permit the attainment of velocities measured in tens of thousands of kilometers per second, i.e., practically comparable to the velocity of light. With this in mind, Kondratyuk expressed a very interesting idea for experimental verification of the Theory of Relativity.**

In the first two decades of the century, however, when Tsiolkovskii, Tsander, and Kondratyuk first expressed their views on the possibility of using nuclear and ionic engines, the question was completely unrealistic, since the level of technological development did not admit the realization of the engines they proposed. Therefore the question of finding a real means of achieving escape velocity continued to confront the researchers.

The second means of resolving this problem amounted to launching an interplanetary ship, not directly from the earth, but from a launching base situated at a considerable altitude, for which, in Tsander's opinion, a large airplane could serve, or, as Tsiolkovskii suggested, an artificial earth satellite. Tsander mentioned intermediate interplanetary stations in the course of his lectures. Kondratyuk had the interesting idea of using as an intermediate base for interplanetary flights an artificial satellite not of the earth, but of the moon.

Such factors as the absence of an atmosphere on the moon and a gravity appreciably less than that of the earth spoke in favor of the last suggestion. As studies carried out in our own time have shown, however, the complexity of constructing such an intermediate base and its considerable distance from the earth constitute supplementary and in themselves sufficiently great difficulties.

In bringing up the idea of making intermediate interplanetary bases of artificial satellites, Tsiolkovskii, Tsander, and Kondratyuk proposed to use them for stockpiling fuel and the necessities for human existence in outer space. This would facilitate the attainment of escape velocity through a real mass ratio, since it would relieve the necessity of including the things indicated (fuel, food supplies, equipment, etc.) in the inert mass of the rocket on the first lap of the flight (earth to intermediate base).

The proposal to use artificial earth satellites and other celestial bodies as intermediate bases for interplanetary flights is extraordinarily far-sighted and is a feature of the majority of contemporary projects to reach other heavenly bodies. Even nowadays, however, this notion, which continues to figure in many projects, has received no practical resolution (because of its complexity); in the period under consideration it was totally unfeasible. The researchers therefore continued their search for a more acceptable solution.

The third means of attaining escape velocity, in whose development Soviet scientists again played a significant role, consisted of using the rocket's inert mass during the flight. It was pointed out above that the flight velocity depends on the ratio of the mass of propellant to the inert mass (mass of the rocket without propellant). But examination of Tsiolkovskii's formula shows that not only an increase in the mass of the propellant but a

* Kondratyuk, Yu. Manuscript (first version), p.65.

** Ibid., p.79. See also the second version of the manuscript, p.32.

reduction in the inert mass of the rocket can influence this relationship. As the propellant is burned, in fact, a considerable part of the inert mass becomes superfluous, and its acceleration requires unproductive expenditure of energy. It will readily be concluded, from what has been said above, that in order to raise the flight velocity, it is necessary, as the propellant is consumed, to discard the superfluous parts of the rocket as quickly as possible, retaining only what is required for its further normal functioning.

As early as the first version of his manuscript, Kondratyuk suggested placing the propellant not in one, but in several tanks, so that as emptied they could successively be jettisoned, thereby reducing the inert mass of the rocket.

He wrote: "Everywhere, where I speak of the activity of a substance, its mass must be regarded as that of the substance plus that of the vessel in which it is contained; when we consume some part of the propellant, we also throw away the vessel that held it. It is therefore better, and perhaps even necessary, not to keep the whole supply of propellant in a single vessel, but in several progressively smaller ones. This is the more practical since a single vessel can hardly offer the convenience of great lightness."*

This thought was expressed more clearly in the second version of the manuscript, to which he prefixed a foreword "To those who will read in order to build":

"It is necessary to make not a single container, but several, for the propellant, since a single such vessel would have a considerable weight and towards the end of the flight, when almost all the propellant was gone, would constitute a mass which, being completely unnecessary, might make the missile several times heavier and would require a great quantity of propellant [for its acceleration — ed.]. It is therefore necessary to make containers of several different sizes. At first, the material from the large ones is used up, then, when they are depleted, they are simply jettisoned, and the following ones are emptied. The dimensions of the containers must be calculated in such a way that the empty weight of the vessel being depleted constitutes, in the case of every vessel, one and the same fraction of the total weight of what remains of the rocket. This ratio must be worked out in conformity, first, with the requirement that it be as small as possible; and second, with the need to avoid an excessively great number of vessels which might make construction of the missile too complicated."**

Subsequently, continuing to improve his project, Kondratyuk suggested building multi-assembly rockets (by assembly he meant the totality of objects required for the normal functioning of a rocket engine).† After thinking over the possibility of decreasing the inert mass of the rocket, Kondratyuk came to the conclusion that this mass was not uniform, but could be divided into two parts: the absolute inert mass P_A, for the purpose of communicating velocity to which the whole rocket is built, and the proportional inert mass P_P, consisting of everything inessential to the functioning of the rocket. To this category belong "the propellant tanks; all the apparatus serving to convey the propellant into the combustion chamber; the

* Kondratyuk, Yu. Manuscript (first version), pp. 36-37.

** Kondratyuk, Yu. Manuscript (second version), pp. 34-36.

† When giving his manuscripts to Vorob'ev, Kondratyuk originally dated the third version 1920, but he subsequently added: "Copied and edited in 1923-24." It is therefore impossible to establish precisely the date of inclusion in the book of the section on the "proportional inert mass."

combustion chambers; the ejection pipe and all parts connecting items from these four categories and reinforcing the whole rocket structure.*

It is evident that by absolute inert (mass), Kondratyuk meant the payload and by proportional inert (mass), the mass of the rocket structure. He pointed out that the first part of the inert mass P_P is the starting point of the rocket design, is settled beforehand, and cannot be substantially changed. The second part P_p, as Kondratyuk showed, must be approximately proportional to the active mass which it serves (hence the name, proportional inert). Here, consequently, were possibilities of reducing the rocket's inert mass.

Designating the relation of the mass of the rocket structure P_P to the mass of the propellant A by q, whose magnitude was determined by the degree of engineering excellence in the construction of the objects P_p, Kondratyuk showed that as the mass of the propellant decreases, the dimensions of the engine, fuel tanks, feed system, and the parts connecting them can be substantially reduced.

On the basis of this idea, he proposed to divide the flight trajectory into several sections, on each of which a different assembly P_P would function (by assembly Kondratyuk meant the totality of objects comprising the proportional inert (mass)). As he pointed out: "In order for the mass of the rocket not to be considerably increased by the presence of the masses P_P and the necessity of imparting to them the same velocity as to P_p, it would be desirable to have a ratio of approximately $q \leqslant \frac{1}{5(N_p-1)}$ or in general, $q \leqslant \frac{1}{5(N_e-1)}$, where N_e is the inert load for that leg over which the assembly P_P continuously functions and at the end of which it can be jettisoned, so as not to burden the rocket with its superfluous weight. After this another assembly P_P of smaller dimensions and weight, corresponding to the reduced masses of propellant and [gas] discharge, begins to function."**

In this manuscript Kondratyuk clearly approached closely the idea of the multistage rocket, though without giving its structural design. The latter was done by Tsiolkovskii, who, continuing to work on the problem of interplanetary flight, came in 1926 to the conclusion that a rocket would be able to attain escape velocity only if it were to receive a comparatively high initial velocity without burning any of its own fuel.

After analyzing the possible means of giving the rocket an initial velocity — using an automobile, steamship, locomotive, airplane, dirigible, gas or electromagnetic cannon, etc.— Tsiolkovskii concluded that these means could not give a velocity of more than 100 to 200 m/sec.

"From which it is evident," he continued, "that to give the projectile a velocity of over 200 m/sec, special means are required... In this case the simplest and cheapest way is to use a rocket or jet: that is, our space rocket must be placed in or on another — land — rocket, which, without itself leaving the ground, gives the desired take-off speed."†

He therefore suggested using a two-stage rocket, whose first stage — in Tsiolkovskii's terminology, the "land rocket" — would move on the earth and in the dense layers of the atmosphere, and whose second stage, the "space rocket," would reach the desired velocity.

* Kondratyuk, Yu. Manuscript (third version), pp. 16-17.

** Ibid., pp. 17-18.

† Tsiolkovskii, K.E. "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Space with Jet Machines), p. 91, Kaluga, 1926.

The theory of multistage rockets was further developed in Tsiolkovskii's book "Kosmicheskie raketnye poezda" (Cosmic Rocket Trains) and in one of the chapters of his manuscript "Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov" (Fundamentals of the Construction of Gas Engines, Motors, and Aircraft,)* which was not published during his lifetime.

Tsiolkovskii suggested two means of attaining escape velocity: a rocket train and a rocket squadron. They had much in common and both consisted of launching of several rockets, only one of which would reach the final goal. The remaining rockets would act as accelerators and would return to earth after their fuel supply was exhausted.

In the first method, however (the cosmic rocket train), the rockets were joined in consecutive order, one after the other, and at a given moment only one rocket, at the head, functioned. After consumption of its fuel the head rocket detached itself from the rocket train, after which the second rocket began to run, becoming the head one, etc.

In the second method (the rocket squadron), the rockets were connected in parallel formation and ran simultaneously, but instead of consuming all of their fuel, used only half of it. At this point the fuel of some of the rockets was transferred to the half-empty tanks of the other rockets, which continued their journey with full fuel tanks. The empty rockets detached themselves from the squadron and returned to the earth. The process of fuel transfer continued until only one rocket was left of the squadron.

Not stopping at the exposition of the principle of the multistage rocket, Tsiolkovskii gave its mathematical theory in detail and demonstrated with scientific rigor the possibility of attaining escape velocity with rocket engines running on chemical fuel, through practically feasible mass ratios.

For a cosmic rocket train he obtained the final formula

$$V = W\left\{\ln\left[1+\frac{1}{\left(1+\frac{1}{z}\right)n-1}\right]+\ln\left[1+\frac{1}{\left(1+\frac{1}{z}\right)(n-1)-1}\right]+\ldots+\right.$$
$$\left.+\ln\left[1+\frac{1}{\left(1+\frac{1}{z}\right)(n-i+1)-1}\right]+\ldots+\ln(1+z)\right\},$$

where V is the maximum ideal velocity obtainable by the given multistage rocket; W is the relative exhaust velocity, constant for all stages; z is Tsiolkovskii's number (the ratio of the mass of the propellant to the mass of the rocket without propellant, constant for all stages; n is the number of stages; and i is the ordinal number of an arbitrary subrocket after the detachment of $(i-1)$ stages.

For a rocket squadron:

$$V = nW\ln\frac{1+z}{1+0.5z}+W\ln(1+z)$$

where the symbols have the same meaning as in the previous equations except that n here designates, not the number of stages, but the number of fuel transfers.

Adoption of the multistage rocket principle permitted resolution of the problem of attaining escape velocity in the shortest possible time. In fact, the experimental stage was reached as early as the 1930's, altitudes of about 400 km were attained, using a two-stage rocket, in the 1940's, and in our own time multistage rockets have achieved widespread use.

* Archive of the Academy of Sciences of the USSR, Folio 555, entry 1, file 105.

The acceptance of this principle, however, did not solve the problem of completely eliminating the harmful effect of the inert mass. The parts which had become superfluous were jettisoned, but without being of any further use. The researchers therefore asked if it might not be possible to use these parts to increase the active mass, as supplementary fuel.

First Tsander, and a few years later, Kondratyuk, gave a positive answer to this question, with a proposal to manufacture the rocket's structural parts out of materials possessing high calorific power, so that they could be used as supplementary fuel.

As has already been pointed out above, Tsander expressed the idea that the structure of the space vehicle could be used for fuel as early as 1909. Subsequently he returned repeatedly to this idea and developed it, even performing experiments on the combustion of molten metals.

In 1924 he first expressed publicly his idea that the solid structural material of the rocket could be used for fuel. Addressing a meeting of the theoretical section of the Moscow Society of Amateur Astronomers on his project for a space vehicle consisting of a combination of rocket and airplane, Tsander indicated the possibility of using the structure of the airplane-carrier as supplementary fuel.

The proposal was echoed in his statement of June, 1924 before the Committee on Inventions, and in the article "Perelety na drugie planety" (Flights to Other Planets) published in July, 1924.

"In my design," Tsander wrote, "the rocket is structurally connected to two airplanes: a large one for ascent, and a second, much smaller, for descent... Structural parts of the larger airplane are used to supplement liquid fuel, since the latter alone is insufficient for the attainment of escape velocity. It is therefore proposed to build the airplane of duralumin, electron, or another similar metallic alloy."*

"While the rocket is in flight," he observed in another work, "the parts of the lifting surfaces (propeller, motor, and the other parts of the airplane), must be pulled in, melted in a special vessel or cauldron, and the molten metal ejected to increase performance."**

The same proposal to use the superfluous structure of the rocket as supplementary fuel is also found in the third version of Kondratyuk's manuscript and in the book "Zavoevanie mezhplanetnykh prostranstv" (The Conquest of Interplanetary Space), which he published in 1929.

In evaluating his multi-assembly rockets, Kondratyuk indicated that their use would permit only a considerable reduction in the harmful influence of the inert mass, but would not eliminate it altogether. However, he envisaged a solution which would make it possible to minimize its influence:

"This solution is as follows: as for a system of several assemblies, a number of assemblies P_n of gradually decreasing size are built; they are made preferably of aluminum (duraluminum), or of silicon and magnesium according to availability; the parts that must be particularly fire-resistant (the internal surfaces of the combustion chamber), are made of appropriate types of coal (carbon). The assemblies that become superfluous, according to size, as the mass of the rocket decreases, are not jettisoned but broken down, and pass to the pilot's cabin to be decomposed and melted to serve

* Tsander, F.A. "Opisanie mezhplanetnogo korablya" (Description of a Space Vehicle). From the book "Problema poleta..." (The Problem of Flight by Jet Propulsion), p. 280. 1961.

** Tsander, F.A. "Perelety na drugie planety" (Flights to Other Planets).— Tekhnika i Zhizn', No. 13, p. 15. 1924.

as chemical fuel components. Such a solution is ideal, since only the last, smallest assembly will remain as a parasitic mass P_p — all the preceding ones are active, and only temporarily perform the function of P_p."*

This proposition of Tsander and Kondratyuk is of considerable interest, since it offers a possibility of increasing the fuel supply on board the rocket, while minimizing the inert mass. The structural realization of the scheme, however, is extraordinarily difficult, and has not found a practical solution at the present day.

In the 1920's three more interesting ideas came from Soviet scientists working on space travel: 1) to use the atmosphere as a braking medium for a landing on the earth; 2) to use the power of solar rays as a source of supplementary energy; and 3) to derive from the gravitational fields of the planets, as the space vehicle flew around them, additional energy and corresponding velocity.

The idea of using the atmosphere as a braking medium was first expressed in print by Tsander, who in his article "Perelety na drugie planety" (Flights to Other Planets) clearly stated the necessity of equipping rockets with small wings for a glide landing on the earth and other planets with an atmosphere. In a series of papers Tsander subjected to detailed examination a number of questions connected with the problem of a spaceship's return to the earth, and gave corresponding calculations.**

It must be recalled that the idea of turning a spaceship into a gliderlike projectile, sui generis, for its return to the earth, is also met in the first versions of Kondratyuk's manuscript, where it is pointed out that such a design would permit a considerable reduction in the quantity of propellant needed.†

Kondratyuk also performed a calculation showing how much less propellant was needed if atmospheric resistance was used to assist landing, and concluded that the means of return indicated by him "give great economy of matter (i.e., we could realize that flight, and even extraordinarily long-range flights with incomparably low expenditure of matter."†† As has been remarked above, however, Kondratyuk's work was unpublished at that period, and remained unknown for a long time.

Tsiolkovskii devoted a great deal of attention to the problem of landing on the earth, and in his manuscript "Kosmicheskii korabl'" (The Spaceship) (1924), he also considered using the atmosphere as a braking medium for a return from outer space. In 1926 this idea was reflected in his printed work "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Cosmic Space with Jet Machines).

The proposal undoubtedly deserves serious consideration, since it permits a real reduction in the quantity of propellant required for the return of a spaceship to the earth.

* Kondratyuk, Yu. Manuscript (third version), p. 20.

** Tsander, F.A. Raschet poleta mezhplanetnogo korablya v atmosfere Zemli (spusk)" (Flight Calculations for the Descent of an Interplanetary Ship in the Earth's Atmosphere), in his book "Problema poleta pri pomoshchi reaktivnykh apparatov" (The Problem of Flight by Jet Propulsion), pp. 382-414, Moskva, 1961; "O temperature, kotoruyu primet mezhplanetnyi korabl' pri planiruyushchem spuske na Zemlyu" (The Temperature Acquired by an Interplanetary Ship Making a Glide Landing upon the Earth), ibid., pp. 424-438.

† Kondratyuk, Yu. Manuscript (first version), p. 22.

†† Kondratyuk, Yu. Manuscript (second version), p. 18.

The idea of using solar energy, found in the earliest versions of Kondratyuk's manuscript, is also of considerable interest. Kondratyuk pointed out the necessity of an arrangement of parabolic mirrors of very great dimensions, made of extremely thin sheets of some good reflecting metal (tin, silver, or nickel), on board the space vehicle.*

Kondratyuk proposed using solar illumination both to meet the needs of passengers (light and heat) and to enhance the energy supply of the space vehicle, by preheating oxygen and hydrogen and deriving these gases directly from water. Furthermore, he pointed out that "if it proves possible to build a jet missile working on the recoil of cathode rays, the sun will be the only source of sufficient energy and the only means of converting it from heat to electrical energy."**

However, Kondratyuk expressed only the idea of using solar energy, without sufficient accompanying details of structural design, let alone approximate numerical calculations; nor did he mention other applications of solar illumination. Tsander gave this matter much fuller and more detailed attention, suggesting that both the heat and pressure of sunlight could be used as sources of energy for space vehicles.

As early as the turn of the twentieth century, P. N. Lebedev (1866-1912) had demonstrated experimentally that light can exert pressure on bodies. On the basis of this thesis, Tsander proposed installing on space vehicles mirrors or screens of extremely thin sheets or special ring-solenoids, inside which was placed iron dust, kept in the plane of the ring by an electric field. Tsander wrote, "If sunlight strikes the mirror, screen, or dust particles, it exerts a definite pressure on them. In the vast distances of interplanetary space, small forces can give rise to comparatively great velocities."†

Tsander seriously pondered the possibility of using light pressure for space flight, and considered this method extremely promising for flights in interplanetary space (for considerable distances from the sun and planets). He determined the magnitude of the specific pressure of light and calculated how big the mirrors would have to be in order to give the space vehicle the necessary velocity. ††

In the second half of 1924, Tsiolkovskii also began to think about using the pressure of sunlight for space flight. Considering means of attaining escape velocity in his manuscript work "Kosmicheskii korabl'" (The Spaceship) Tsiolkovskii went further and concluded that it was possible to build a quantized engine: "Finally," he wrote, "there is a third, most enticing means of obtaining velocity, communication of energy to the projectile from outside, from the earth. The projectile itself need not store up material (i.e., ponderable, in the form of explosive or propellant) energy. Energy is transmitted to it from the planet in the form of a parallel bundle of short-wave electromagnetic rays. If the wavelength does not exceed a few dozen centimeters, such electromagnetic "light" can be directed in a

* Kondratyuk, Yu. Manuscript (first version), p. 70.

** Kondratyuk, Yu. Manuscript (second version), p. 121, obverse.

† Tsander, F.A. "Perelety na drugie planety" (Flights to Other Planets). — Tekhnika i Zhizn', No. 13, p. 16, 1924.

†† On this see Tsander's manuscript "O primenenii tonchaishikh listov dlya poletov v mezhplanetnom prostranstve" (The Use of Very Thin Sheets for Flights in Interplanetary Space) published in the book: "Problema poleta pri pomoshchi reaktivnykh apparatov. Mezhplanetnye polety" (The Problem of Flight by Jet Propulsion. Interplanetary Flights), pp. 361-376, Moskva. 1961.

parallel bundle, with the help of a large concave (parabolic) mirror, to the flying airplane, where they eject air particles or "dead" reserve material, so as to impart escape velocity while still in the atmosphere. This parallel bundle of electromagnetic or even solar light rays should itself produce a pressure (whose existence is still doubted, however), which can also give the projectile sufficient velocity. In such a case there is no need of reserves for ejection."*

It is worth mentioning that the Soviet scientists working on the problem of space flight not only discussed the possibility of using solar energy, but also worked out quite correctly the periods in which engines of different type should function. They showed that in leaving the earth and returning to it, i.e., at times when the earth's gravity potential must be overcome, and a considerable acceleration communicated to the space vehicle, the energy of chemical fuel must be used; but once in orbit and in outer space, at a considerable distance from the earth, it was desirable to use solar energy.

"We therefore conclude," explained Tsander, "that it would be necessary to apply the great thrust of the rocket with the enormous accompanying fuel consumption only for departure from the earth's atmosphere and acceleration to a velocity of 8 km/sec, and subsequently only for rapid changes of direction to avoid meteor showers... And furthermore, in interplanetary space, on account of the enormous distances and the adequacy of small thrust, it is far better to use free light pressure or light energy transmitted at a distance by means of very thin mirrors."**

The same idea, though expressed in a somewhat different form, is found in Tsiolkovskii's manuscript "Kosmicheskii korabl'" (The Spaceship). Dwelling on the difficulties of exploiting the pressure of a stream of rays, and admitting that the resolution of these questions would have to be left to the future, Konstantin Eduardovich remarked: "But the pressure of sunlight, electromagnetic waves, electrons, and helium nuclei (alpha rays) can immediately be adapted in the ether for projectiles that have already overcome the earth's attraction and left the atmosphere, and that will only later on require an increase in velocity. In a vacuum, when there is already motion, this velocity can be increased as slowly as desired, so that here, no energy is needed and the insignificant pressure of light and positive or negative electrons (α and β rays) can be exploited."†

Kondratyuk wrote on the same subject: "In aircraft the most efficient method for exploitation of solar illumination is as follows: for departure and return, propellant should be used, since at those times considerable acceleration is necessary, but between them solar illumination is preferable."††

In the works of Soviet scientists at the period being considered, questions of astronavigation were also touched upon. Tsander was foremost in this area, and as early as 1908 considered the question of how many days it would take to reach Mars and Venus. He also set himself the theoretical problem of determining the laws of motion from one point of space to

* Tsiolkovskii, K.E. "Kosmicheskii korabl' " (The Spaceship).– Archive of the Academy of Sciences of the USSR, Folio 555, entry 1, file 46.

** Tsander, F.A. "Perelety na drugie planety (stat'ya vtoraya)" (Flights to Other Planets (second article) in the book "Problemy poleta pri pomoshchi reaktivnykh apparatov. Mezhplanetnye polety" (The Problem of Flight by Jet Propulsion. Interplanetary Flights), p. 277, Moskva, 1961.

† Tsiolkovskii, K.E. "Kosmicheskii korabl'" (The Spaceship).– Archive of the Academy of Sciences of the USSR, Folio 555, entry 1, file 47, sheets 10 and 10 obverse.

†† Kondratyuk, Yu. Manuscript (first version), p. 73.

another with the requirement that "1) the work done and 2) the time expended be minimum." *

Later on Tsander returned repeatedly to the problems of astronavigation, continuing to broaden and deepen his research in this area. By 1925 he had worked out in some detail such questions as the motion of a spaceship in the gravitational fields of the sun, the planets, and their satellites, the determination of trajectories and duration of flight, and the magnitude of the additional velocities required for their realization.**

In particular, he proposed choice of a flight trajectory that would permit exploitation of the gravitational fields of the planets and their satellites to increase velocity, and calculated the velocity increments that could be obtained by flying around each of the planets in the solar system.†

During the first third of the twentieth century Soviet space flight theoreticians laid the foundations of the mechanics of bodies of variable mass, and of the theory of space flight, and made a number of highly interesting proposals, including:

1) The use of liquid-propellant rocket engines.

2) The use of metallic propellants of high calorific power.

3) The use of other forms of energy, e. g., atomic and electrojet engines, solar pressure.

4) The creation of intermediate interplanetary bases in the form of artificial satellites of the earth and other celestial bodies.

5) The use of multi-assembly and multistage rockets.

6) The use of the structural material of the rocket itself as supplementary fuel.

7) The use of wings for glide landings on the earth and other planets possessing an atmosphere.

The analysis of these proposals testifies to the high level attained by Soviet scientists working on the theory of astronautics, and gives grounds for the belief that as early as the end of the 1920's, the foundations of a theory of interplanetary flight had been laid in the USSR.

* Zander, F. Die Weltschiffe ..., p. 7-8.

** All of this research must have been included in the book "Perelety na drugie planety. Pervyi shag v neob'yatnoe mirovoe prostranstvo." This book was not published during Tsander's lifetime, however. The sections mentioned were first published in 1961, in the book "Problema poleta...", pp. 285-360, Moskva, 1961.

† Ibid., p. 340.

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I. A. Merkulov

A CONTRIBUTION TO THE HISTORY OF THE DEVELOPMENT OF SOVIET JET ENGINEERING DURING THE 1930's

(Iz istorii razvitiya reaktivnoi tekhniki v SSSR v tridtsatye gody XX veka)

The first manned space flights are among the great achievements of modern science and technology.

In praise of the remarkable scientific exploits of the first cosmonauts, A. A. Blagonravov (Academy of Sciences of the USSR) wrote:

"... space flight is not the accomplishment of a single man. It involves creative search and the strenuous effort of tens of thousands of people, it embodies lofty attainments in many fields of Soviet science and engineering...

"Space ships and carrier rockets are essentially the central achievement of contemporary science and engineering..."*

The building of rockets for space exploration was the result of many decades of stubborn, selfless, and inspired effort on the part of space flight enthusiasts and rocketry amateurs. At present, therefore, in the years of the greatest successes in the mastery of outer space, it is interesting to learn how rocketry grew in Russia.

More than 30 years have already passed since the students and disciples of K. E. Tsiolkovskii began systematic scientific research and experimental work on the design of rocket aircraft. In 1929–1930 they began to experiment with liquid-propellant jet engines and thus laid the foundations for the rapid development of Soviet rocket engineering. In 1929 the construction of experimental jet engines was begun at the Leningrad Gas Dynamics Laboratory (GDL), where a series of the first liquid-propellant rocket engines in the USSR were built in 1930–1931. In 1930 F. A. Tsander conducted firing tests of his first experimental jet engine, running on gasoline and compressed air, and in 1932 a scientific rocketry center was organized in Moscow. It was given the name GIRD, i. e., Jet Propulsion Study Group (Gruppa izucheniya reaktivnogo dvizheniya). As long ago as 1933 GIRD built and successfully tested the first Soviet liquid-propellant rockets. These rockets were the precursors of great scientific ventures into space.

From GIRD and GDL emerged the experts who assured the future development of Soviet rocketry and prepared the ground for the USSR's splendid attainments in space.

Clarification of the glorious history of Soviet rocket engineering is advisable in order to reaffirm the historical truth in print. In recent years

* "Izvestiya," No. 188. 1961.

publications repeatedly appearing in the western press have carried the assertion that the development of Soviet rocketry began only after the Second World War, as a result of the acquaintance of Soviet specialists with German rocketry.

Actually, as the facts show, the USSR was not only the birthplace of the theory of jet propulsion, but was the first country to develop broad, government-planned experimental research in the field of rocketry.

The labors of the Soviet scientists who laid the foundations of rocketry in the 1930's were very fruitful. Many interesting scientific ideas emerged at that time, and a number of successful working designs were born in those scientific societies. But Soviet scientists, whose lofty goal was the realization of space flight, modestly evaluated their first attainments, and printed practically nothing about their early successes. The work on rocket engineering going on abroad at that time, however, was widely publicized in the press, and sometimes results expected in the future were given out as if already obtained. The foreign newspapers of those years were full of sensational reports about supposed discoveries and inventions of the greatest importance in the field of rocket propulsion, and even about preparations to send rockets to the moon. The exposure of one groundless sensation did not interfere with the publication, after a time, of another even farther removed from reality. This difference in the reporting of Soviet and foreign efforts gave rise to the mistaken assumption that rocketry developed slowly in the USSR.

To everyone familiar with the laws of technical development it is perfectly clear that in the logical chain of astronautics development: theory of jet propulsion— prolonged experimental research— space flight, the middle link cannot be omitted. Without this link, the contemporary successes of Soviet science in space would have been impossible.

The object of this article is to discuss the experimental research on rocket aircraft carried out in the USSR in the 1930's.

The development of Soviet rocket engineering is one of the most interesting chapters in the history of science and engineering. This chapter remains to be written by the combined efforts of many scientists who have witnessed and participated in great accomplishments. It is not the present author's intention, in so short an article, to give an exhaustive description of all the work done on jet engines and rockets. In spite of the great successes attained, rocket design is still a very young branch of engineering. It has not yet been possible to evaluate properly many facts in the history of rocket engineering, and in the case of several events no concordant view has yet been formed.

Practically nothing has been written of the history of Soviet rocket engineering. The material introduced in this work, therefore, may be regarded as one of the first attempts to assemble brief reports on the first jet engines and rockets constructed in the USSR.

It was the author's good fortune to take a modest part in the work of GIRD, working under the direction of its organizers, and to learn rocket engineering directly from the GDL and GIRD experts who laid its foundations. Subsequently the author worked for several years in the Jet Group of the Central Council of Osoaviakhim. This article will also include a description of the jet engines and rockets which the author saw during his years of work in GIRD and in the Jet Group.

THE BEGINNING OF PRACTICAL WORK

From the earliest days of its development Soviet rocket engineering has had a broadly public character.

As long ago as 1924, at the Air Force Academy im. N. E. Zhukovskii, in Moscow, a Space Travel Section, with a total membership of 25, was organized.

The Section set itself the goal of popularizing the idea of space travel, organizing a laboratory for rocket engine planning and testing, and publishing the magazine "Raketa." K. E. Tsiolkovskii attentively followed the work of this group.

In May, 1924, the Section was reorganized as a Society for the Study of Space Travel. It organized a lecture, given by M. Ya. Lapirov-Skoblo in the Polytechnic Museum on the theme "Interplanetary Travel." After this lecture about 200 people enrolled in the society.

On 4 October, 1924, F. A. Tsander delivered an interesting lecture on the theme "Flight to Other Worlds" in the great lecture-hall of the Physics Institute of Moscow University. On 31 October, Professor V. P. Vetchinkin delivered a lecture on space travel in the Polytechnic Museum. The lecture of this famous scientist, one of the students of N. E. Zhukovskii, and a continuer of his work, made a great impression on those that heard it.

The Society for the Study of Interplanetary Communications did not exist for long, but it did much for the popularization of astronautics and rocketry.

"The Society's major service," wrote its chairman, G. Kramarov, "was that as early as 1924 it united the forces of many talented engineers, designers, and inventors interested in space travel. . ."*

In 1928, in Leningrad, the Gas Dynamics Laboratory (GDL) of the Military Scientific Research Committee of the Revolutionary War Council of the USSR was founded. In this laboratory the first construction of rocket engines running on high-quality solid fuels was begun by a group of rocketry amateurs: N. I. Tikhomirov, B. S. Petropavlovskii, G. E. Langemak, and V. A. Artem'ev.

On 15 May, 1929, a Department of Electrical and Liquid-Propellant Rocket Engines was organized in GDL, and began theoretical and experimental research. GDL's many years of systematic work played a great role in the birth and development of liquid-propellant rocket engines in the USSR.

In 1931, a group of scientists and engineers applied to the Chairman of the Central Board of Osoaviakhim with a proposal to organize work on rocketry within the system of Osoaviakhim. The proposal of this enterprising group was adopted, and in the same year a Jet Engine Section of the Aviation Engineering Bureau of the Central Board of Osoaviakhim was founded, with F. A. Tsander as its director.

In the second half of 1931 this section was reorganized as the Group for the Study of Jet Propulsion— GIRD. Similar groups began to appear in other cities. The most successful one working simultaneously with the Moscow group was that of Leningrad— LenGIRD, organized in 1931 with the active participation of Professor N. A. Rynin. There were thus two rocketry societies working in Leningrad in those years: GDL and LenGIRD.

* "Komsomol'skaya Pravda," 19 August, 1961.

For the most part the people in GIRD were young scientists, engineers, designers, and workers who had decided to dedicate their lives to the development of rocketry and the realization of space travel. In its first months GIRD was occupied, for the most part, in publicizing rocketry and bringing together the experts interested in it. The Moscow group, being the most numerous and the most successful, soon came to be called Central — TsGIRD [Tsentral'naya GIRD].

A great role in the scientific publicizing of jet propulsion and the ideas of astronautics was played by the remarkable books of Soviet scientists. Among these the works of K. E. Tsiolkovskii must be placed in the first rank. His books not only brought knowledge to wide circles in the scientific and engineering community, but also solved a great organizational problem. By publishing in his books his correspondence with many people, Tsiolkovskii facilitated acquaintance between those interested in space travel.

At the end of the 1920's and beginning of the 1930's the nine-volume work of Professor N. A. Rynin, "Mezhplanetnye soobshcheniya" (Space Travel) was published in Leningrad. This was a real encyclopedia of astronautics, containing the history of the problem of space travel and all of the theoretical work on jet propulsion and astronautics known at that time.

In 1929 a very interesting book by Yu. V. Kondratyuk, "Zavoevanie mezhplanetnykh prostranstv" (The Conquest of Interplanetary Space), was published in Novosibirsk, and in 1932 F. A. Tsander's book "Problema poleta pri pomoshchi reaktivnykh apparatov" (The Problem of Flight by Jet Propulsion) appeared in Moscow. Many interesting new ideas, which retain their topicality to the present day, were set forth in these two books.

Interesting books by the Germans Max Valier and E. Sänger, and by the French scientist Maurice Roux, were translated into Russian. Valuable help in publicizing the problem of astronautics was also given by the popular-science books, brochures, and articles of Ya. I. Perel'man, Professor K. L. Baev, and many other scientists and popularizers.

At the beginning of 1932, on the initiative of TsGIRD, special courses in rocket engineering and design were organized in Moscow. Noted Soviet scientists gave lectures in this distinctive short-term institute. V. P. Vetchinkin gave a very interesting course on the dynamics of jet aircraft. B. M. Zemskii gave a course of hydrodynamics and gas dynamics, and B. S. Stechkin gave a fundamental course of lectures on his own theory of jet engines. These lectures served as a guide for the design of the world's first jet engines. N. A. Zhuravchenko gave a very clear course of experimental aerodynamics. At that time the directors of GIRD already saw manned space flight as their goal, and their program therefore included a course on the physiology of high-altitude flight, given by one of the founders of aeronautical medicine, Dr. Dobrotvorskii. Many other interesting lectures were given. In this way, with rocketry still in its infancy, GIRD prepared experts to deal with the problems of a new and complicated sphere of knowledge. In those same years Professor K. A. Putilov established a Department of Gas Dynamics, as one of the theoretical foundations of rocketry, at Gor'ki University.

In April, 1932, GIRD set up a scientific research center for rocket engineering at 19 Sadovo-Spasskaya Street in Moscow. Here the construction of jet engines and rockets was begun, with the support of noted Soviet scientists. Members of GIRD and many other inventors then working on rocketry constantly received help, support, and valuable advice from

B. N. Yur'ev and B. S. Stechkin, of the Academy of Sciences of the USSR, Professors V. P. Vetchinkin, A. V. Kvasnikova, F. I. Frankl', and other scientists.

At the end of 1933, as a joint venture of GDL and GIRD, a scientific center was organized and it began combined operations in Moscow in 1934. In the same year the All-Union Conference for Study of the Stratosphere, convened by the Academy of Sciences of the USSR, took place in Leningrad. At the conference a good deal of attention was devoted to high-altitude rockets. The USSR's first conference on the use of rocket craft for study of the stratosphere took place in 1935.

The support scientists gave to the first advances in the new field did much to promote the successful development of the work in progress. The directorates of GDL and GIRD performed a great service in choosing the proper scientific direction for their work and concentrating the efforts of the societies on the solution of the most important fundamental problems. First among these problems was that of rocket power engineering— the building of reliable rocket engines running on the most efficient liquid propellants.

THE FIRST SOVIET ROCKET ENGINES

The first experimental research on liquid-propellant rocket engines in the Soviet Union began at the end of the 1920's and was carried on by both the Leningrad and Moscow groups.

The Moscow group was headed by one of the pioneers of Soviet rocket engineering, Fridrikh Arturovich Tsander, who was one of the first disciples of K. E. Tsiolkovskii. Working at TsAGI, F. A. Tsander and his assistants built and successfully tested the ER-1 jet engine in 1930. The engine ran on gasoline and compressed air, fed into the chamber from a cylinder. This experimental model was therefore a jet engine running on liquid propellant and a gaslike oxidizer. Under thermal conditions, when the temperature of the gas in the combustion chamber was raised, the character of its phase transitions made the ER-1 resemble a jet engine.

The tests of the ER-1 engine were good preparation for the construction of rocket engines running on a liquid propellant and liquid oxidizer. As Tsander pointed out in the foreword to his book "Problema poleta pri pomoshchi reaktivnykh apparatov," this arrangement was of great value as a "model which demonstrated the practical possibility of obtaining reactive force with completely satisfactory efficiency." After the successful experiments with the ER-1 engine Tsander designed the ER-2. The construction of this engine was completed on 23 December, 1932, and firing trials began on 18 March, 1933. The ER-2 engine, running on gasoline and liquid oxygen and developing a thrust of 50 kg, was intended for installation in an experimental jet airplane. Tsander's premature death on 28 March, 1933, put an end to the fruitful work of this talented inventor, but his friends and students continued the work he had begun and built a great many jet engines running on alcohol and liquid oxygen.*

* For more details of their work see the article of E. K. Moshkin, below (p. 156 et seq.).

The group of scientists working at the Gas Dynamics Laboratory in Leningrad also attained great successes in the construction of liquid-propellant rocket engines. On the basis of the theoretical and experimental research carried out in 1929-1930, this group in 1930 developed the first Soviet liquid-propellant rocket engine ERM-1.* This engine (Figure 1) ran on a liquid propellant and liquid oxidant. As propellant, toluene or gasoline was used, and as oxidant, nitrogen tetroxide or liquid oxygen. This was the first Soviet liquid-propellant rocket engine in the full sense of the words.

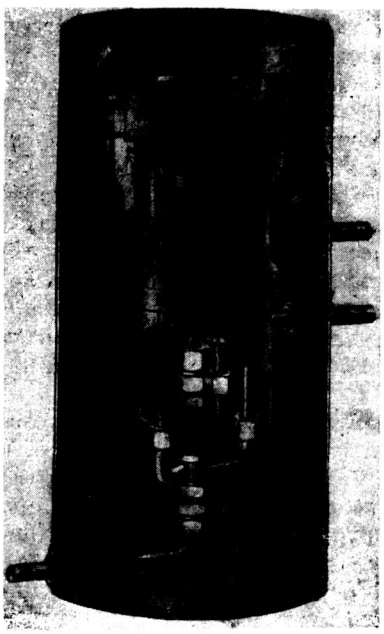

FIGURE 1. The first Soviet liquid-propellant rocket engine (ERM-1)

The ERM-1 was built and tested in 1931. On the test stand it developed a thrust of 20 kg. Nineteen thirty-one is therefore noteworthy as the year in which the first Soviet liquid-propellant rocket engine was constructed and successfully tested.

The ERM-1 engine had a cylindrical steel combustion chamber, internally plated with a thin sheet of copper, and interchangeable cylindrical steel nozzles, also copper-plated, with throat diameters of 10, 15, and 20 mm. The junctions of chamber and nozzle were hermetically sealed by a knife-edged gasket with two steel rings. Six jets — three for the oxidant and three for the fuel, alternately arranged — were grouped in a single circle at the tip of the combustion chamber. To protect them from corrosion the copper nipples were plated with gold over their entire surface. The liquid fuel components were fed to the jets through Dural tubing. Dural check valves with lattice filters were placed at the mouth of the jets. The combustion chamber with the adjacent tubing was enclosed in a water-filled sleeve for cooling. The entire engine comprised 93 parts. In trials it was installed on the stand with the nozzle upwards. The fuel was fired by alcohol-soaked wadding previously introduced into the combustion chamber and ignited through the nozzle by a Bickford safety fuse.

In 1931 GDL built and stand-tested an experimental liquid-propellant rocket engine (ERM), running on a liquid mono-propellant. A mixture of liquid fuel (gasoline, benzol, or toluene) and oxidant (nitrogen textroxide) was used. The combustion chamber of this rocket was equipped with electrodes for ignition, a safety valve, and a crushing device for measuring the pressure. Forty-six stand firing tests of ERM engines were performed in 1931, and in the same year the ERM-2 engine was developed and built.

Among the important achievements of GDL scientists was their theoretical and experimental research of 1929-1930, which demonstrated the fundamental efficiency of an electrical jet engine, propelled by solid or

* [Opytnyi raketnyi motor (Experimental rocket engine).]

liquid conductors exploded by an electric current in a chamber with a nozzle.

In subsequent years GDL's extensive experimental research on liquid-propellant rockets resulted in the development of methods for reliable fuel ignition and means of impactless launching. One means of reliable ignition in the engines constructed at that time consisted of using gunpowder charges as a powerful source of fire which would assure the rapid combustion of the fuel mixture. In 1931 very efficient means of chemical ignition, which have since become widespread in rocketry, were proposed. Fuel combustion was promoted by introducing into the combustion chamber a chemical substance which flashed upon coming into contact with the fuel or oxidant. In the same year the use of self-igniting fuel was proposed. In order for combustion of the fuel components to take place instantly upon contact without any supplementary effect, corresponding additives had to be supplied. There exist fuels and oxidants which burn upon contact without special additives. Nowadays self-igniting fuels are widely employed in liquid-propellant rockets.

Much attention was given to the question of the protracted reliable functioning of liquid-propellant rockets. In the first place this required the development of a sure cooling system for the combustion chamber and the nozzle. Soviet designers built rockets capable of running for an extended period of time, with cooling systems based on Tsiolkovskii's idea of using one of the fuel components to cool the engine.

In 1932 a series of engines from ERM-4 to ERM-22 were designed to develop systems for the mixture of liquid oxidants and propellants as well as methods of ignition and launching suitable for operation on various fuels. In the course of the year, the ERM-4, ERM-5, and ERM-8 engines were subjected to 18 test-stand firings, and the ERM-9, ERM-11, ERM-12, and ERM-16 underwent even more.

In 1933 GDL planned a whole series of liquid-propellant rocket engines (from ERM-23 to ERM-52), running on kerosene and nitric acid. Nitric acid was used as an oxidant both in pure form and mixed with oxides of nitrogen. More than 100 test-stand firings were conducted with these engines, and one of them, the ERM-50, with chemical ignition, developed a thrust of 150 kg in the 1933 tests, and was selected for an experimental rocket. In the same year the ERM-52 engine, which developed a thrust of 300 kg, was stand tested and chosen for a more powerful high-altitude rocket and for a naval torpedo.

Between 1934 and 1936 the same group developed a series of even more perfect engines (ERM-53 to ERM-66). In 1936 official static tests of one of the best liquid-propellant engines of that time, the ERM-65, took place. This engine ran on kerosene and nitric acid, and its thrust could be regulated within the range of 50 to 175 kg. For ground operation it was nominally rated at 155 kg and its economy was high. For the nominal combustion chamber pressure of 22 atmospheres, it consumed 0.738 kg of fuel per second, and the specific pulse was therefore 210 seconds.

Fuel was fed into the combustion chamber from tanks under a maximum pressure of 35 atmospheres. Pyrotechnic ignition, i.e., by means of a grain ignited by an electric squib, was used. The combustion chamber and the nozzle were cooled externally by nitric acid, and the combustion chamber head was cooled internally by propellant components entering the chamber.

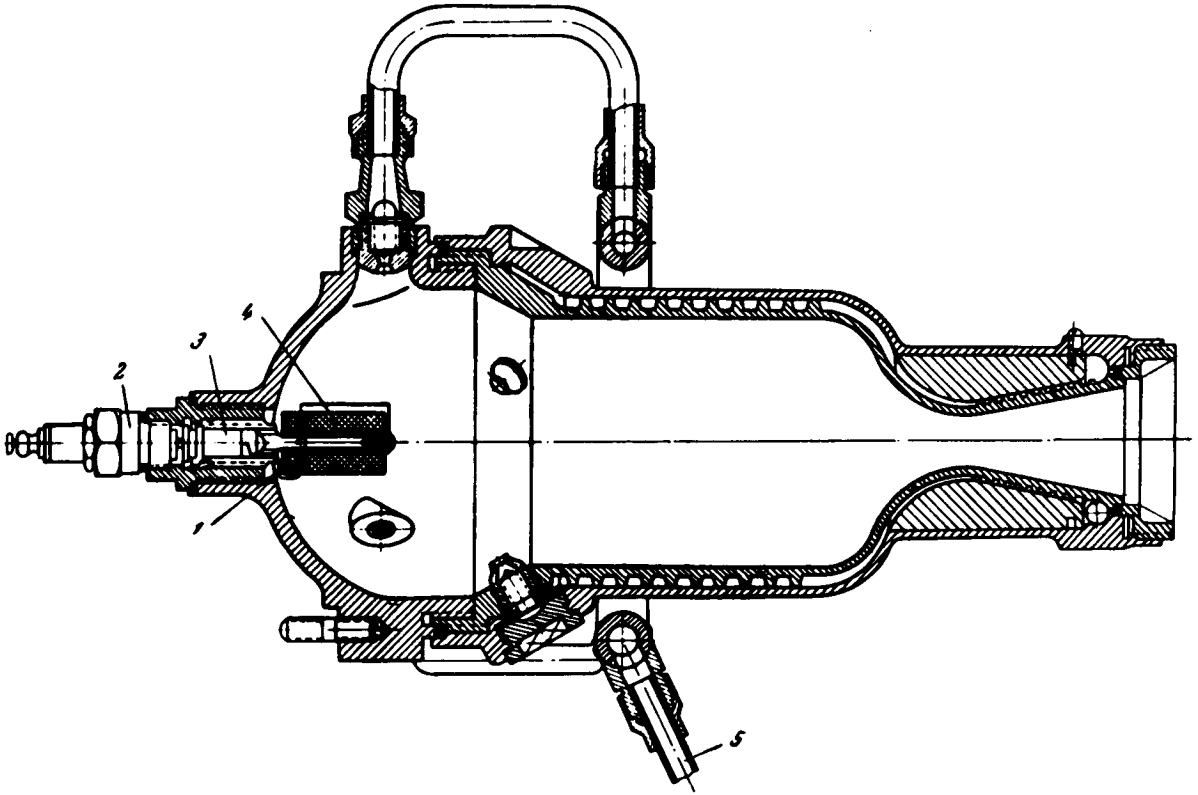

FIGURE 2. Chamber of the ERM-65 liquid-propellant rocket engine

1-combustible compound; 2-ignition plug and current collector; 3-electric squib; 4-ignition grain; 5-fuel feed

The ERM-65 engine weighed a total of 14.26 kg and was 465 mm long, with a chamber diameter of 175 mm. The maximum diameter of the engine, including the manifolds attached to the chamber, was 345 mm. The combustion chamber volume was 2015 liters.

The structural details of this engine are shown in Figure 2. The combustion chamber consisted of three major steel parts: the head, the chamber and nozzle, and the housing, threaded together and intersealed on an asbestos packing. The surface of the combustion chamber head, which was internally cooled, had a working temperature of 300 to 400°C. The chamber and nozzle was externally cooled, and was fitted with a screw ribbing on both parts of it to increase the thermal output. The necessary clearance between housing and nozzle was assured by the installation of two aluminum liners, attached to each other by two pins, and to the housing by a locking screw.

The nozzle was equipped with a compensator— a lead packing, tightened by a threaded annulus. The compensator did not obstruct the thermal expansion of the chamber and nozzle (when this occurred, the lead flowed out into the annular gap between the housing and the chamber and nozzle), and assured an airtight seal. After each test the annulus had to be tightened to restore the hermetic seal.

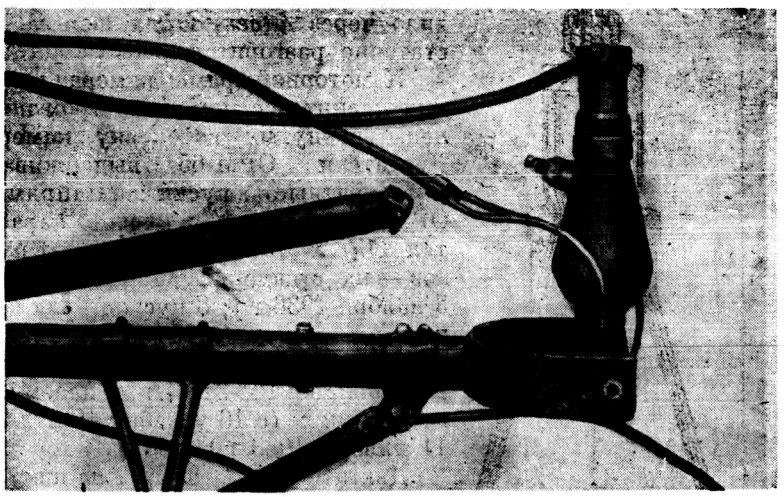

FIGURE 3. A rocket engine, running on alcohol and liquid oxygen, on the test stand

The propellant components were injected into the combustion chamber by centrifugal jets (three for the oxidant and three for the fuel).

The oxidant jets were set in the forward part of the chamber and nozzle at an angle of 60° to the axis and directed toward the head. The propellant jets were set in the head perpendicular to its axis. In a circular arrangement the oxidant jets alternated with the propellant jets every sixty degrees. The worm swirl vanes of the jets were fastened to them by a short left-handed thread screwed on to right-handed helical ribs, to prevent its becoming unscrewed during operation.

Cruciform slots on the flat end of the bodies of the oxidant jets were designed to screw them to the chamber. The jets in the chamber head were sealed with aluminum packings, and those in the chamber and nozzle, with lead. The feed pipes were sealed with lead packings. The ignition system comprised an ignition plug with current collector, a cartridge chamber with electric squib, and a pyrotechnic ignition grain.

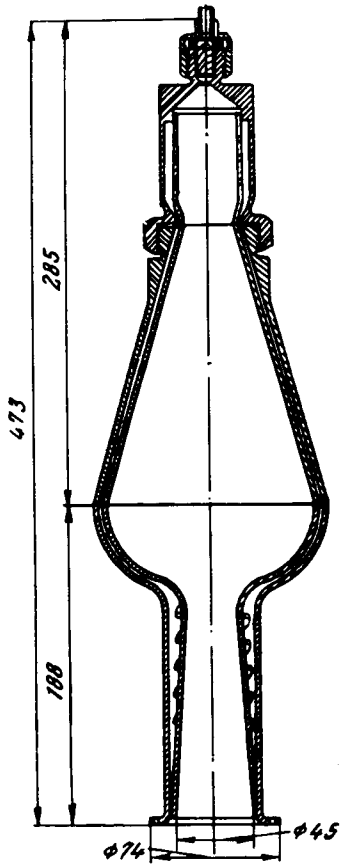

FIGURE 4. Sectional view of a rocket engine

The electric squib had a resistor which burned out when the circuit was closed, igniting the ballistite inside the squib. The incandescent gases flowed through ducts in the cartridge case, igniting the grain at its flat end, and the burning ignition grain fired the propellant components entering the chamber through the jets. The feeding of the components took place only after the grain had been successfully ignited. This was accomplished by a low resistance shunt admitted through an aperture in the grain, and included in the ignition circuit in parallel with the indicating light on the control panel, or by means of an automatic starter. When the shunt burned out the light was heated to incandescence, and this either served as a signal for the propellant valves to be opened manually, or activated the automatic starter. The distance from the shunt to the butt of the grain was so chosen that the grain would be sufficiently kindled during the 4 seconds it took the shunt to burn out.

The combustion chamber was fastened to the engine frame by means of three pins twisted into the head of the chamber. The ERM-65 ran for a total of 30.7 minutes in 49 launchings, including 20 on the test stand (between 17 September and 5 November, 1936); it underwent 8 additional launchings in an aerial torpedo (from 29 April, 1937, to 8 October, 1938), and 21 in land trials of the rocket-propelled aircraft PR-318-1 (between 16 December, 1937, and 11 January, 1938).

The No. 2 ERM-65 engine, in its sixth launching, on 11 March, 1938, ran continuously for 230 seconds in the land trial of a rocket-propelled aircraft. In its fourteenth launching, on 29 January, 1939, it propelled an aerial torpedo in flight. The flight tests of the aerial torpedo with the ERM-65 engine were repeated on 8 March, 1939. Documents record that the engine ran normally during these trials. Detailed description of the ERM-65 gives a clear idea of the level of development reached by Soviet rocketry in those years.

In 1937 another series of liquid-propellant rocket engines, running on kerosene and nitric acid, with a thrust of 150 to 300 kg, was built, and two

engines with thrusts of 80 and 100 kg, running on kerosene and tetranitromethane, were developed. At the same time, alcohol and liquid oxygen engines, one of which is shown in Figure 4, were successfully developed.

Between 1932 and 1941 more than 100 rocket engines of various types were designed in the USSR, and the successes attained permitted many aerial rocket launchings as early as the first half of the 1930's.

THE FIRST SOVIET ROCKETS

In 1933 GIRD designed and constructed four types of liquid-propellant rockets, designated by the numbers 05, 07, 09, and 10.

On 17 August, 1933, GIRD 09 became the first Soviet rocket to fly into the heavens (Figure 5). It was 2.4 meters in length, 180 mm in diameter, and had a launching weight of 19 kg, of which 6.2 kg was pay load (equipment and parachute), and 5 kg, propellant.

The engine of the 09 rocket ran on liquid oxygen and "solid" gasoline (a solution of rosin in gasoline, constituting a gelatinous mass). Its developed thrust was 52 kg and it ran for 15 to 18 seconds. In 1933-1934 six rockets of this type (Figure 6) were successfully launched. In the first launching the rocket reached an altitude of 400 meters, and 1500 meters was attained in subsequent launchings.

On 25 November, 1933, the launching of a second rocket, GIRD-X, depicted in Figure 7, took place. The rocket had a length of 2.2 meters, diameter of 140 mm, and launching weight of 29.5 kg, of which 8.3 kg was propellant (alcohol and liquid oxygen), and 2 kg, payload. Its engine developed a thrust of 70 kg and ran for 22 seconds. The estimated altitude attained was 5500 meters.

The rocket was cigar-shaped with a pointed nose-cone. Its tail was equipped with four oblong Dural stabilizers, almost half as long as the rocket main body.

The entire rocket consisted of five compartments, of which the first contained the parachute with the ejection apparatus. The second contained the oxygen tank, and the third, a two-liter vessel of compressed air at a pressure of 150 atmospheres. The fundamental launching equipment of the rocket was also kept there (a safety valve for the compressed air, an air-feed tap, a manometer, a nonreturn oxygen valve and an oxygen tap). The fourth section was an alcohol tank, through which the liquid oxygen pipes passed, and the fifth (and lowest) was for the engine and the manifolds through which the propellant components passed into the combustion chamber.

The design of the 07 rocket, in which the engine was located above the center of gravity, required disposition of the fuel tanks in the stabilizers. Each of the four stabilizers contained one tank: in all, two for oxygen, and two for alcohol (Figure 8).

This rocket was 2 meters in height, and had a launching weight of 35 kg, of which propellant was 10 kg, and payload, 2 kg. The engine developed a thrust of 85 kg.

The first Soviet rocket trials were of great value as the raw material of future development, and permitted a practical realization of high efficiency in all structural rocket components, especially the engine. The

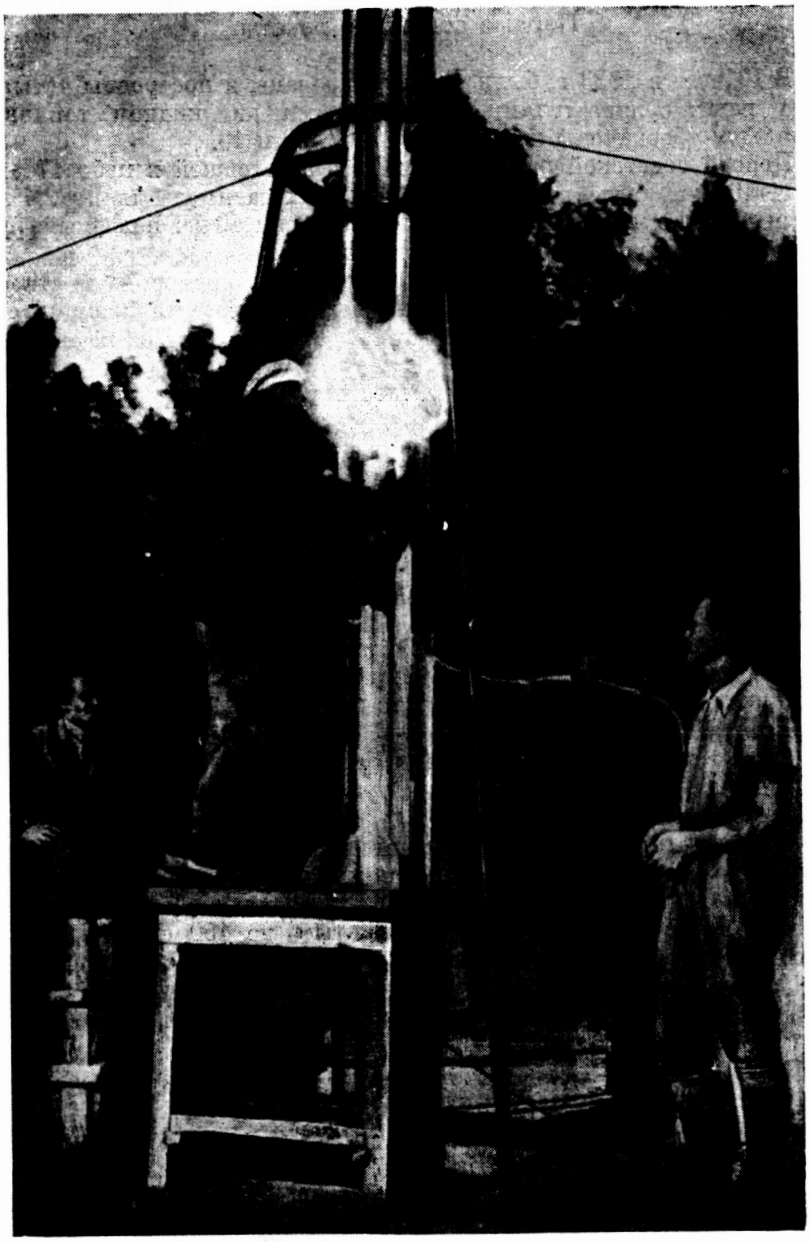

FIGURE 5. Oxygen refuelling of the first Soviet rocket (09)

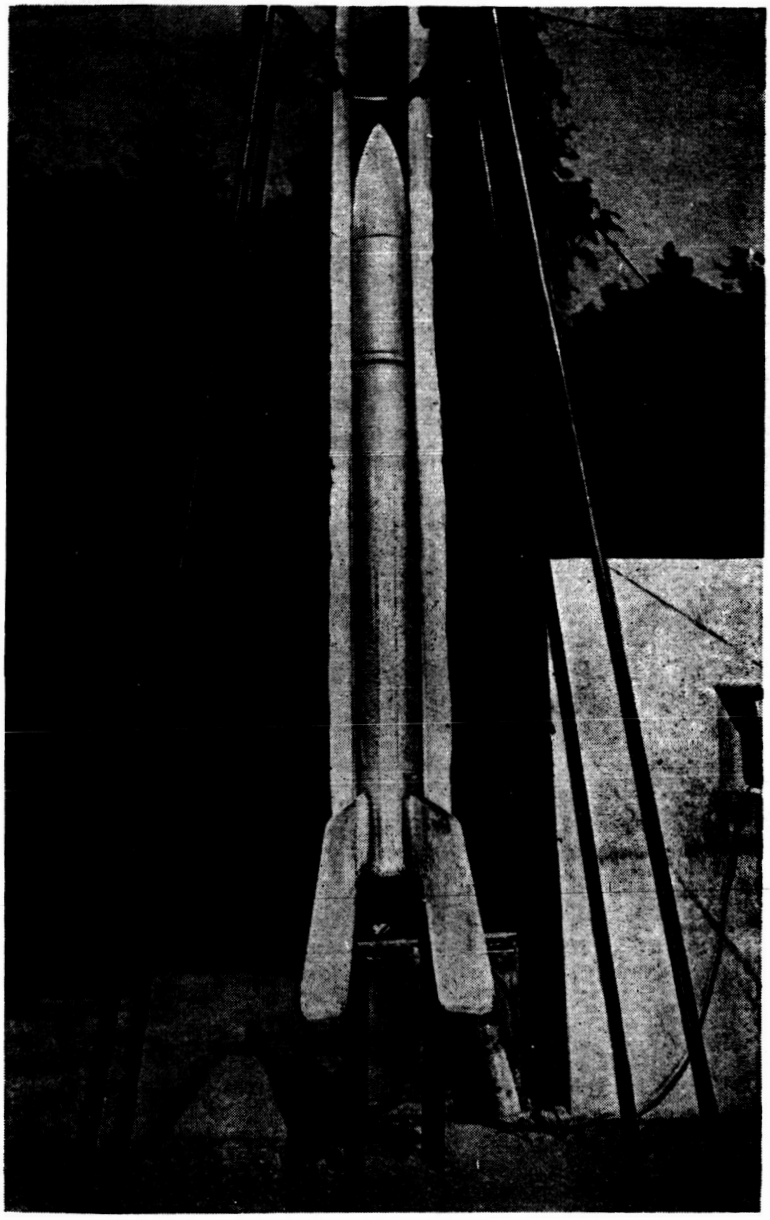

FIGURE 6. The first Soviet rocket on the launching stand

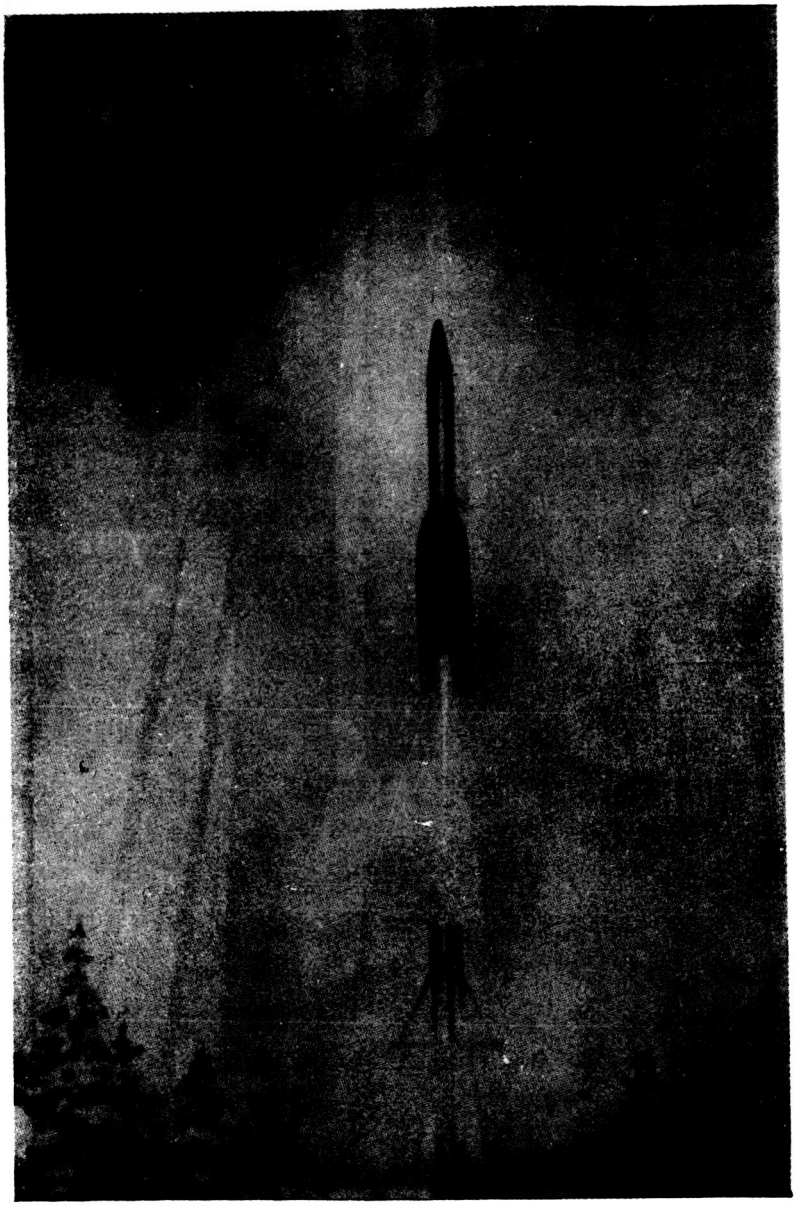

FIGURE 7. The "GIRD-X" rocket

results of the trials also gave a more precise direction to subsequent design and research, and GIRD's experience with the earliest rockets was the foundation of future Soviet rocket engineering.

FIGURE 8. The 07 rocket

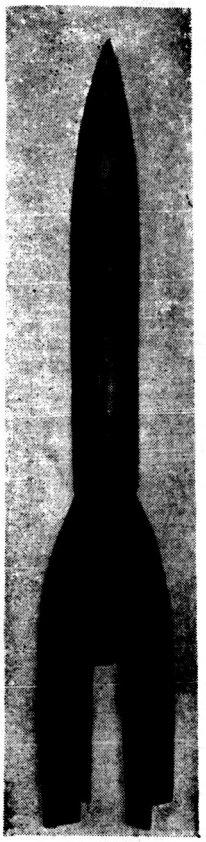

FIGURE 9. Rocket with engine running on alcohol and liquid oxygen

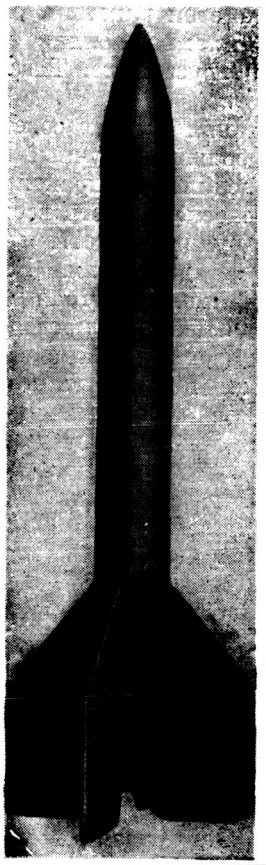

FIGURE 10. Rocket with four fuel tanks

In 1937 a group of designers who had detached themselves from GIRD conducted flight tests of yet another type of rocket (Figure 9). It was 2.3 m in length, 200 mm in diameter, and had a launching weight of 39 kg, with an engine developing 100 kg of thrust. In many of the tests performed over the course of three years, this rocket attained an altitude of 5000 meters. The first design was improved by reduction of the launching weight to 30.5 kg, and the length to 2.18 meters. The diameter remained the same. The constructional innovation of this rocket was the use of nonmetallic materials. Rockets of this type covered a distance of 7000 meters in inclined flights, and reached altitudes of 3500 to 5000 meters in vertical launchings.

The same group built a rocket with a composite engine, which started on solid propellant, then switched to a liquid propellant consisting of

FIGURE 11. The rocket of the Jet Section of the Stratosphere Committee

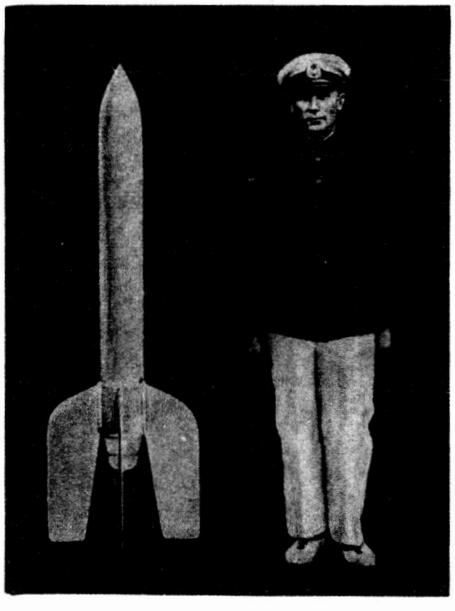

FIGURE 12. The Jet Section's second rocket

alcohol and liquid oxygen. This rocket weighed 10.5 kg, was 1.32 meters in length, and had a diameter of 126 mm. During the first series of tests, in 1938, the engine ran only on solid propellant, and altitudes of 2000 meters were attained.

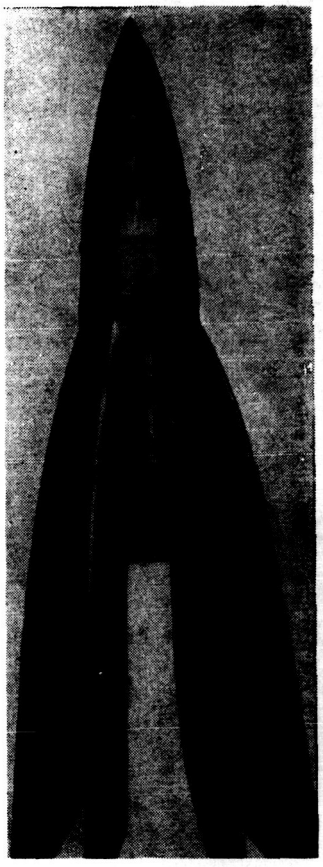

FIGURE 13. The LenGIRD rocket

The group next designed and began construction of a two-stage rocket, with an expected range of 150 kilometers. The rocket had a launching weight of 100 kg, the dry weight of the first stage being 41.5 kg, and that of the second, 7.5 kg.

The GIRD group designed and flight-tested yet another series of rockets (Figure 10) in 1936–1937. This rocket weighed 97 kg (propellant 33 kg, payload about 10 kg), and was 3.2 meters long and 300 mm in diameter, with a thrust of 300 kg. Four parallel fuel tanks were located in the rocket main body

At the beginning of 1939 the same group successfully launched a series of small rockets, with a weight of 12.2 kg, of which 2.4 kg was propellant, and 2 kg, payload. These rockets were 1.285 meters in length and 126 mm in diameter. They attained an altitude of 3000 meters.

In 1940–1941, a series of very large rockets, with launching weights of 180 to 187 kg (59 kg propellant and 25 to 30 kg payload), were flight-tested. These rockets were 3.12 meters in length and 203 mm in diameter. They had a composite engine which ran on solid propellant for 0.86 seconds, producing a thrust of 3840 kg, and then for 10 seconds on a liquid propellant, composed of kerosene and nitric acid. During the test firings the rockets were launched at an angle to the horizon and covered ranges of up to 20 km.

As Soviet rocketry developed on the combined base of Gird and GDL, the Scientific Center was transferred to the industrial system. The directorate of GIRD, however, took a hand in seeing that the work they had begun on the popularization of jet propulsion and the attraction of a wide sector of the population to creative activity in that field was not neglected. At their initiative, a Jet Propulsion Section, based on a large group assembled by GIRD, was organized within the Central Council of Osoaviakhim. This section functioned from 1934 to 1938, first within the system of the Military-Science Committee, and then as part of the Stratosphere Committee.

The section continued to work at popularizing rocket engineering, published scientific literature, prepared engineering personnel for work in the field of rocketry, and designed rockets. It was staffed by amateurs, who did all the general work, combining it with rocket manufacture or study in the institutes. An active part in the work of the section was also taken by outstanding rocketry experts, foremost among whom were the managers

of GIRD and professors V. P. Vetchinkin, B. S. Stechkin, K. A. Putilov, A. V. Kvasnikov, K. L. Baev, B. M. Zemskii, and F. I. Frankl'.

In 1935 the Jet Section constructed and tested a liquid-propellant rocket (Figure 11) 1.64 meters long and 126 mm in diameter, with a take-off weight of about 10 kg. Its engine, running on alcohol and liquid oxygen, developed 40 kg of thrust, and the estimated altitude attained was 4500 meters. They built another rocket (Figure 12), with an alcohol and liquid oxygen engine in 1937. In addition, water was introduced into the chamber, somewhat diminishing the specific thrust, but facilitating cooling.

Rocket design and construction also went on in Leningrad, and in 1933 GDL scientists built and stand-tested a rocket with kerosene and nitric acid engine. The rocket was 1.88 meters in length and 195 mm in diameter, and it developed 200 kg of thrust.

A rocket of original design was constructed by LenGIRD in 1935 (Figure 13). Its engine comprised two combustion chambers, which rotated about the rocket's longitudinal axis. This was accomplished by the use of nozzles with an oblique edge. The horizontal component of thrust also contributed to the rotation of the chambers about the rocket axis. Rotation was employed to compress the fuel (consisting of gasoline and liquid oxygen) inside the chambers by means of centrifugal force.

FIGURE 14. First-stage solid-propellant rocket

In 1939 a two-stage rocket, whose first stage consisted of a solid-propellant rocket (Figure 14), and whose second stage was a jet-engined rocket, was built and tested. The rocket had a launching weight of 7.07 kg (3.51 kg for the first stage, and 3.56 kg for the second). It was first successfully tested on 5 March, 1939, and another test with precise measurement of altitude took place on 19 May, 1939, at which time the rocket attained an altitude of 625 meters with the first-stage engine. At this point, at a velocity of 105 m/sec, the second-stage engine was started, and the

solid-propellant first stage, detached from the second by means of an air brake, fell to earth. The second stage, thanks to its jet engine, reached a velocity of 224 m/sec and an altitude of 1800 meters. This was the world's first jet-engined rocket (Figure 15). Altogether sixteen launchings of such rockets took place in 1939.

FIGURE 15. Second-stage jet-engined rocket

Many more Soviet rockets built and tested in the 1930's might be described.

The earliest rockets, as the figures cited show, reached altitudes of only a few kilometers and had no practical application. Their construction and testing, however, demonstrated the feasibility of building rocket engines and rocket-engined aircraft, and revealed the fundamental problems facing rocket designers and the difficulties that would have to be overcome.

After the first tests work in rocketry came to be concentrated on engine research, the study of liquid-propellant combustion processes, engine starting, combustion chamber cooling, fuel feed systems, and engine control. Much outstanding work was done on rocket dynamics and resolution of flight stability problems.

During the following ten years work in rocketry was, as a rule, confined to laboratories, experimental design bureaus, and proving grounds. During these years a rich store of experimental material was accumulated, and it became the basis for the liquid-propellant jet rockets, which began to be built for study of the stratosphere about the middle of the 1940's.

THE FIRST JET AIRCRAFT FLIGHTS

As early as 30 years ago GIRD began to work on the realization of manned rocket aircraft flight. Tsander intended his ER-2 engine for installation in a glider designed by B. I. Cheranovskii, and GIRD, after the glider's acceptance flight, gave it the designation GIRD RP1, and prepared it for tests as a rocket-propelled aircraft (Figure 16). It had a wing span of 12.1 meters, length of 3.09 meters, height of 1.25 meters, wing area of 20 square meters, aspect ratio of 7.3 meters, and weight (without rocket engine) of 200 kg.

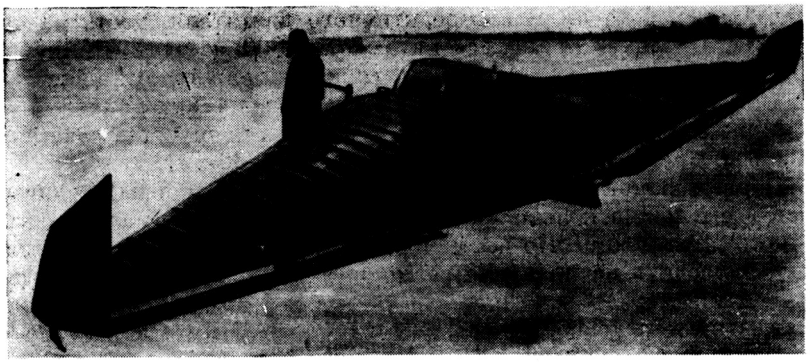

FIGURE 16. The GIRD rocket-propelled aircraft

In February, 1940, the pilot V. K. Fedorov completed flights in the SK-9 aircraft with liquid-propellant rocket engine. Much preparatory work preceded the test flight. The rocket engine underwent thorough stand testing

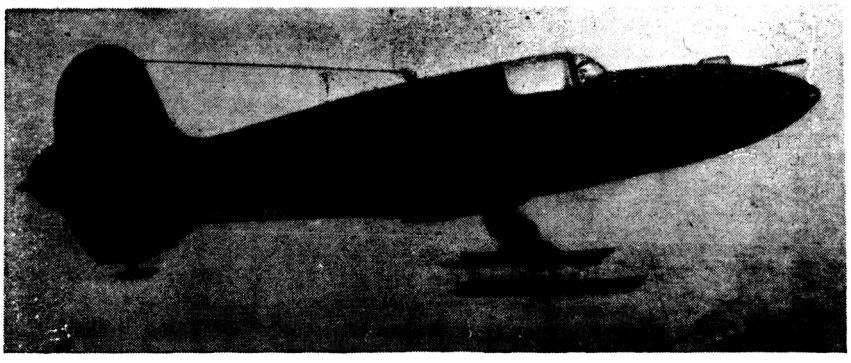

FIGURE 17. Fighter aircraft with liquid-propellant rocket engine

before being installed in the SK-9 glider. In October, 1939, successful captive-flight tests, with the engine installed in the glider, were carried out and it was decided to proceed to trial flights. In order to make the flight as protracted as possible, for the most thorough testing of the engine's aerial performance, the rocket-propelled aircraft was towed to an altitude

of 2 km by an ordinary airplane. At this altitude Fedorov separated and began independent flight. When he was at a sufficient distance from the tow-plane he engaged the rocket engine, which flew stably until all its fuel was consumed, at which point the pilot made a safe glide landing at the airfield.

These flight trials were an important step in the development of fast jet fighter aircraft. In 1941 V. F. Bolkhovitinov designed a jet fighter with liquid-propellant rocket engine. Bolkhovitinov's airplane (Figure 17) was an easylift midwing monoplane of composite design with retractable landing gear. The nose end of the fuselage had two 20-millimeter guns with ammunition, and radio equipment. Behind this section was the pilot's cockpit, covered by a canopy, and the fuel tank compartment. The rocket engine was located in the tail.

Flight tests of the new airplane began in September, 1941. At first only the airplane's aerodynamic qualities were tested, and for this purpose, it was towed, without an engine, behind a Pe-2 aircraft. On 15 May, 1942, test-pilot G. Ya. Bakhchivandzhi completed the first flight with the rocket engine. The airplane left the airfield under its own power and rapidly gained high altitude. After completing the prearranged flight route, Bakhchivandzhi landed safely. After him other pilots also flew this jet fighter.

Concurrently with the testing of aircraft with liquid-propellant rocket engines, work was being done in the USSR on the construction of jet engines for aviation. The first to be tested were ramjet engines, and in 1939 two of them were installed as supplementary engines in the I-15-bis fighter plane designed by N. N. Polikarpov. The plane was flown by test-pilot P. E. Loginov. He gained the prescribed altitude, reached maximum velocity, and started the jet engines. By 1939, the problems of engine starting in flight and stability of combustion had been resolved, and the pilot was able to switch the jet engines on and off, regulating their thrust, several times in the course of the flight. The I-15-bis jet-engined aircraft was officially flight-tested on 25 January, 1940.

FIGURE 18. The "Chaika" airplane with supplementary jet engines

In 1940 ramjet engines of greater size were tested in another of Polikarpov's aircraft, the I-153 (Chaika) (Figure 18). Besides P. E. Loginov, N. A. Sapotsko, A. V. Davydov, and A. I. Zhukov were participating

test-pilots. Their flights of 1939 and 1940 were the world's first in jet-engined aircraft.

A. M. Lyul'ka, who, beginning in 1934, developed a series of jet engine designs with compressor and gas turbine, was one of the most outstanding and original Soviet aviation designers. He determined the engineering characteristics of these engines and showed that they were the most efficient aero-engines over a very short period of time. The form taken by foreign projects for several years was determined by his 1937 design for a turbo-jet engine with axial-flow compressor and annular combustion chamber.

The successful construction of gas turbine jet engines was facilitated by the valuable theoretical contributions of Soviet scientists, and in particular, of B. S. Stechkin (Acad. Sci. USSR), and of professors V. M. Makovskii, V. V. Uvarov, A. V. Kvasnikov, K. A. Ushakov, G. S. Zhiritskii, V. I. Dmitrievskii, K. V. Kholshchevnikov, V. Kh. Abiants, and others. Their work provided a foundation for the remarkable turbo-jet engines built by groups of Soviet aviation engineers.

THEORETICAL FOUNDATIONS OF ROCKETRY

The most important determining factors in the success of Soviet rocket engineering were the correct choice of a direction for future research, and the extensive theoretical preparations for dealing with the problems of rocketry. The theoretical foundations of jet propulsion were laid as long ago as the turn of the twentieth century.

In the 1930's Soviet scientists continued the development of theory, and their contributions are important enough to merit as much discussion as their experimental work on rocket engines and aircraft. Insofar as the theoretical studies of the thirties were a continuation of earlier work, these earlier contributions must first be recalled.

The scientists working on the problem of space flight concentrated their attention on its basis, rocket power engineering, and K. E. Tsiolkovskii dealt with this subject in his works.

Since the propellant is the rocket engine's source of energy, Tsiolkovskii made the question of propellant a central problem in his very first works on jet propulsion. His was the idea of building a rocket engine running on liquid propellant, whose energy yield would be more efficient than that of the solid propellants then in use. Tsiolkovskii had a number of interesting ideas, some of which have already been realized, while others are still awaiting practical application, in the theory of rocket propellants. For example, he proposed using hydrogen as a fuel, with oxygen and ozone, more efficient than pure oxygen, as oxidant.

Tsiolkovskii's ideas were further developed by his students and disciples. Yu. V. Kondratyuk suggested using high-calorific compounds of boron hydride as fuel for a liquid-propellant rocket engine. In 1930, at GDL, suggestions were first made for the use of nitric acid, nitrogen tetroxide, hydrogen peroxide, perchloric acid, tetranitromethane, and the solutions of one of these in another, as oxidants in rocket engines. It was also proposed to use not only oxidation reactions, but other exothermic reactions (i. e., reactions accompanied by the liberation of heat), such as fluorination reactions, as well. Kondratyuk and Tsander had the fruitful idea of supplementing

liquid rocket propellant with metallic fuel, which would increase the thermal effect of the reaction, and would, furthermore, make it possible to use as fuel the metallic parts of the rocket, such as empty fuel tanks, which were no longer otherwise serviceable. The creation of a propellant theory for liquid-propellant rocket engines is the outstanding achievement of the Soviet school of rocketry.

The maximum thermal effect is not the only requirement for rocket propellant. The working efficiency of gas depends on its temperature, pressure, and specific volume. The products of combustion must therefore have not only a high temperature, but as great a volume as possible, or, to be more precise, minimum molecular weight. Other characteristics of the propellant, such as its safety in operation and storage, cost, adaptability to mass production, etc., are also important. All these questions were thoroughly worked out by the Soviet scientists who constructed the fundamental theory of rocket propellants. Outstanding research in this area was published by the Air Force Academy im. N. E. Zhukovskii as early as 1936, in the book "Liquid Propellant for Jet Engines." In this major work the following proposition was set down as an immutable law of rocketry: "Efficient propellant is a matter of the first importance. Before the development of a jet engine is undertaken, the most suitable propellant— fuel and oxidizer— must be chosen. The qualities of the engine, and sometimes the success of the entire enterprise, depend upon how well this choice is made."

N. G. Chernyshev (D. Sc. Eng.) made a great contribution to the theory of rocket propellants. A good deal of interesting research on the problems of building rocket engines and selecting appropriate propellants was published in the collections "Jet Propulsion" and "Rocketry," which appeared during the 1930's.

After choice of the most efficient propellant, the problem of making maximum use of its energy, and actually obtaining in practice the thermal effect which the fuel is capable of yielding upon combustion, arises; in other words, combustion must be complete.

The assuring of complete combustion in rocket engines turned out to be one of the most complicated problems. The conditions of fuel combustion in rocket engines were completely different from those in the furnaces of steam boilers or in the cylinders of piston engines. A rocket engine of small dimensions could perform an enormous amount of work. The reason for such great efficiency in these engines was found in the exceptionally great thermal load of their combustion chambers, surpassing everything known in engineering up to that time. In the most perfect steam boilers about 15 calories per second corresponded to each liter of furnace capacity, and in piston aero-engines the magnitude of the thermal load was about 30 cal/l · sec. In liquid-propellant rocket engines it was 1000 cal/l · sec and more. Such a great thermal load could be realized only through very high speed of combustion. In some types of liquid-propellant rocket engines the propellant particles were in the combustion chamber only for thousandths of a second, in the course of which evaporation, activation, and complete combustion had to take place. The construction of rocket engines therefore required profound study of the kinetics of chemical reactions and a search for means of assuring complete combustion for great reaction velocities new in thermal engineering.

The assurance of an efficient combustion process and exhaustion of the combustion chamber were the most important problems in rocket engine construction, and study of combustion processes was necessary for their successful resolution. A series of scientific conferences was devoted to combustion problems, and foremost among them, to combustion processes. The most prominent scientific associations worked on the solution of this problem. An exceptionally valuable contribution to the science of chemical reactions, and in particular, of combustion processes, was made by the groups of Soviet scientists working under the direction of N. N. Semenov (Acad. Sci. USSR), L. N. Khitrin, and A. S. Predvoditelev (corresponding members of the Academy of Sciences of the USSR) and a number of others. The proper scientific organization of their work in rocketry, and concentration of attention on rocket power engineering, permitted Soviet scientists and designers to build high-quality engines running on efficient propellants, and was the foundation of future successes.

A second most important problem in rocketry and in the whole question of cosmonautics was accurate launching of the rocket into its prescribed orbit. For this purpose methods for precise calculation of the boost phase trajectory are required. This is related to questions of rocket dynamics, which is based upon the mechanics of solids of variable mass. Rocket dynamics served as the theoretical foundation of rocketry just as aerodynamics constituted the theoretical foundation of aviation. The development of rocket dynamics was therefore an important prerequisite to the realization of space flight.

The role of rocket dynamics was not limited to the precise calculation of rocket motion. Study of the equations of rocket motion permitted the determination of optimum flight conditions, under which the rocket would enter its space orbit with minimum energy losses. The study of rocket flight dynamics was therefore directly connected with the problem of rocket power engineering, and the combined solution of these problems has significantly contributed to successes in the conquest of space.

While the rocket is gaining velocity, i. e., on the boost phase trajectory, it is subjected to the action of the engine's thrust, and the forces of gravity and air resistance. At every moment of its vertical climb the acceleration of the rocket is defined by the equation

$$j = \frac{R - X - G}{M},$$

where R is the thrust; X, the force of air resistance; G, the force of gravity; and M, the mass of the rocket.

For oblique rocket flight, the equations of motion are given in projections on to the tangent to the trajectory and its normal:

$$j = \frac{R - X - G \sin \theta}{M};$$

$$\frac{V^2}{r} = g \cos \theta,$$

where θ is the angle made by the trajectory with the horizon; r, the radius of curvature of the trajectory; V, the velocity of the rocket.

The problem of calculating the boost phase trajectory consists of the integration of these equations. This problem is analogous to the fundamental problem of exterior ballistics, though considerably more complicated,

since in the case of a rocket, unlike that of a missile, the force of thrust is operating, and the mass of the rocket, because of the consumption of fuel, is a variable.

The basis of the mechanics of bodies of variable mass was worked out by Professor I. V. Meshcherskii. In 1897 he established the fundamental equation of motion for a point of variable mass

$$M\frac{dV}{dt} = F + \frac{dM}{dt}(U - V),$$

where M is the mass of the rocket; V, its velocity; t, the time; F, the resultant of all external forces acting on the rocket; and U, the absolute velocity of the ejected particles.

This equation is of great fundamental importance in the history of the development of theoretical mechanics and especially in rocket dynamics. For the special case of constant mass, Meshcherskii's equation becomes Newton's Second Law, true only for material points of constant mass.

At that time K. E. Tsiolkovskii was carrying out mathematical studies of rocket motion, and in 1903 he published the fundamental theory of rocket motion in his remarkable work, "Issledovanie mirovykh prostranstv reaktivnymi priborami". Tsiolkovskii derived the equation

$$\frac{M_0}{M} = e^{\frac{V}{W}},$$

where M_0 is the initial mass of the rocket, and W, the relative exhaust velocity of the gas particles.

Some highly successful work on the mechanics of bodies of variable mass and the theory of rocket motion was done in the USSR in the 1930's. F. A. Tsander, who took great interest in this problem, worked out the dynamics of ballistic rockets, and urged their use for the high-speed transport of peacetime cargoes. V. P. Vetchinkin, who constructed the dynamics of winged jet craft, made an important contribution to the theory of jet propulsion. His remarkable research was published in the collection "Reaktivnoe dvizhenie". Vetchinkin was not formally affiliated with GIRD, but ideologically he belonged with them. All of GIRD's workers regarded him as a friend, and he often dropped in there, taking an interest in the work and giving assistance in the form of valuable advice on the organization of rocketry work. He was especially helpful in resolving some of the complex theoretical problems confronting the workers of GIRD.

Much of the work done at GIRD was published during the 1930's in the collections "Reaktivnoe dvizhenie" and "Raketnaya tekhnika," for example, L. S. Dushkin's detailed article "Osnovnye polozheniya teorii reaktivnogo dvizheniya" (Fundamental Propositions of the Theory of Jet Propulsion) was printed in No. 1, and "O vertikal'nom polete rakety" (Vertical Rocket Flight) by L. S. Zuev, in No. 2.

Yu. V. Kondratyuk's brilliant paper "Zavoevanie mezhplanetnykh prostranstv" (The Conquest of Interplanetary Space), published in 1929, also made a valuable contribution to the theory of space flight and to rocket dynamics. In this book he studied the application of Tsiolkovskii's equation to multistage rockets, including rockets with an infinite number of stages, i. e., continuously jettisoning superfluous tanks. In this last case the equation of

rocket motion took the form

$$\frac{M_0}{M} = e^{(1+\varepsilon)\frac{V}{W}},$$

where ε is the ratio of the weight of the tanks to that of the propellant.

In his book "Vvedenie v kosmonavtiku" (Introduction to Cosmonautics), published in 1937, A. A. Shternfel'd gave the solution of a number of interesting problems of rocket dynamics.

In 1938 the present author derived the equation of motion of a rocket for the widespread case of incomplete expansion of the gas in the nozzle ("Reaktivnoe dvizhenie," No. 3). Tsiolkovskii's equation is true for rocket motion outside the atmosphere. The case when the pressure of the discharging gases at the lip of the nozzle is infinitely small was therefore considered, although it would apply only to a nozzle of infinite diameter. For a nozzle of finite diameter, rocket designers, in calculating thrust, took into account, besides the force numerically equal to the product mw, the force

$$P = S_c(P_c - P_0),$$

where S_c is the nozzle mouth area; P_c and P_0 are respectively the magnitudes of the static gas pressure at the lip of the nozzle and in the surrounding space.

Considering the action of this force, the author obtained Tsiolkovskii's equation in the form

$$\frac{M_0}{M} = e^{\frac{V}{W+P/m}},$$

where m is the fuel consumption per second.

Professor A. A. Kosmodem'yanskii and his students did much interesting research on the mechanics of solids of variable mass. This subject, created by Meshcherskii and Tsiolkovskii and further developed by other Soviet scientists, became a part of the theoretical foundation of rocketry. A precise calculation of rocket motion, however, requires knowledge of the forces acting on the rocket, among which is the force exerted by air on the rocket main body during its flight through the atmosphere. A precise determination of the forces of air resistance is required for the correct calculation of the boost phase trajectory of space rockets. Consequently, aerodynamic studies have an important place in the accurate calculation of rocket boost.

Since the velocities of space rockets are many times greater than that of sound, the calculation of their motion involves supersonic aerodynamics. This area, which has been greatly developed in the past few decades, has become an independent scientific discipline known as gas dynamics.

Gas dynamics is not limited to the determination of the forces of air resistance, but also aims at discovery of aerodynamic aircraft shapes which minimize the resistance of the medium during the boost phase. It is also a function of gas dynamics to seek the best shapes for external rudders and exhaust control-vanes. Beyond study of the external shape of rockets, a series of gas-dynamical questions relating to the engine, for example the calculation of gas flow through the nozzle, or through the gas turbine of a turbo-pump assembly, had to be resolved.

To sum up, the successful solution of a good many gas-dynamical problems in rocket design has great influence upon actual attainments in rocketry.

In order to make the necessary calculations for a supersonic aircraft, determine the lift of its wings, assure the reliable functioning of controls, and compute the loads affecting it, the motion of solids with supersonic velocities in a gas, or, what amounts to the same thing, the laws of supersonic gas flow about solids contained in the gas, must be studied.

The peculiarities of the motion of air or another gas, with supersonic velocities, were indicated as early as 1902 in the papers of an outstanding Russian scientist, Sergei Alekseevich Chaplygin. His classical paper "O gazovykh struyakh" (Gas Streams) was the foundation of the science of supersonic gas flow.

After its foundation by Chaplygin in the 1930's, gas dynamics developed rapidly. Papers by many of the world's scientists, and several outstanding Soviet ones, appeared: N. E. Kochin, M. V. Keldysh, B. S. Stechkin, S. A. Khristianovich, A. A. Dorodnitsyn, G. I. Petrov (Acad. Sci. USSR), Professor F. I. Frankl', and others. Their work gave Soviet aviation and rocketry means of calculating the forces acting on a solid in a supersonic air stream, and made possible the choice of the most efficient shapes for supersonic aircraft, as well as determination of the flow region in rocket engines.

The work of Soviet scientists in rocket power engineering, rocket dynamics, and gas dynamics, the cardinal scientific problems of rocketry, laid the theoretical foundation of contemporary achievements in the conquest of space.

The three problems mentioned are fundamental in rocketry: the attainment of a given velocity, the ensuring of high accuracy in launching the rocket into its orbit, and the solution of all the gas-dynamical problems required for the satisfaction of the first two requirements. Simultaneously with their solution, Soviet scientists worked fruitfully, both in the thirties and in more recent years, on the development of many other fields of science and engineering that contributed to successes in rocket engineering. Foremost among these were advances in metallurgy, which gave the rocket designers durable alloys characterized, in particular, by high resistance to heat and vibration. Studies on the theory of elasticity and the resistance of materials were also important and equipped rocket designers with very precise methods of designing rockets for strength and solidity. Among them, work on the theory of thinwalled envelopes, and the theory of vibration stability should be recalled.

A very great role was played by Soviet work on automation and remote control. The installation of automatic equipment on board the rocket should serve to assure its keeping strictly to the calculated trajectory. The flight of the third Soviet cosmic rocket gives an example of the amazing accuracy obtained through the use of automatic equipment. Equipment installed on this rocket, and on an automated interplanetary station conveyed into space, governed the flight around the lunar station, precise orientation of the station in space, photography of the other side of the moon, and transmission of the photographs obtained to earth.

Many more problems of science and engineering, tackled by Soviet scientists in the early years of the development of rocket engineering, might be mentioned.

N66 37130

A. A. Kosmodem'yanskii

K. E. TSIOLKOVSKII (THE CHARACTER OF HIS DISCOVERIES AND HIS CREATIVE MANNER)

(Mysli o K. E. Tsiolkovskom (kharakteristika otkrytii i tvorcheskogo stilya))

Tsiolkovskii lived the heroic life of a researcher, and his story arouses amazement and admiration. His scientific activity was many-sided and original: he made outstanding discoveries in aerodynamics, the theory of aviation, rocket dynamics, the theory of space travel, geophysics, and biology. His works include original but disputable articles on philosophy, linguistics, and even on the problems of public life on artificial islands floating around the sun between the orbits of Mars and Jupiter. In 1929 Tsiolkovskii published the rigorous theory of flight of multistage rockets or rocket trains, which turned out to be, both in the USSR and abroad, the basis for the construction of intercontinental ballistic rockets, the first artificial earth satellites, and the first artificial planets in the solar system.

However, this great man, even in his own country, was regarded until his sixtieth year as an eccentric and self-taught dilettante. From 1880 to the end of his life he taught mathematics and physics in a secondary school to make a living. His scientific articles began to appear in print in 1891, and most of his works, before 1917, appeared in the form of small pamphlets, published at Kaluga in meager editions, and at the author's expense. It is Tsiolkovskii's authentic cri de coeur that his scientific ideas were so poorly publicized, while he worked under incredibly difficult material and moral conditions. Only after 1925, when his works began to be translated into foreign languages, did Tsiolkovskii's name become known in Western Europe and America.

In the annals of the history of science few people with such a broad understanding of natural phenomena and technical development, with such a penetrating mind and naive, ardent faith in the power of science, or with such great scientific productivity, can be found.

Konstantin Eduardovich Tsiolkovskii was born on 17 September, 1857, in the village Izhevskoe, Spasskii County, Ryazan Province, the son of a forester. His childhood was clouded by serious illness. In his tenth year, at the beginning of the winter, he contracted scarlet fever and through complications suffered almost total loss of hearing. His deafness did not permit the boy to continue his studies at school, and from the age of 14 he began to study independently, using the books in his father's library. At that period he began to display a passion for invention: he made balloons by glueing together thin sheets of paper, made a small lathe, and built a carriage moved by wind blowing on sails. Between the ages of 16 and 19

Tsiolkovskii lived as a student in Moscow, working independently in the libraries and performing the school chemistry experiments in a dark damp corner, which he rented from a laundress.

During these years Tsiolkovskii had the idea of conquering cosmic space by means of centrifugal force. "I was so excited, even overcome," he wrote later, "that I did not sleep the whole night, but roamed about Moscow, thinking constantly about the great consequences of my discovery, but by morning I had already convinced myself that it was false. My disappointment was as great as my delight had been. That night left its mark upon my entire life; thirty years later I still sometimes dream that I am rising to the stars in my machine, and I feel the same delight as on that immemorial night."*

In 1879 Konstantin Eduardovich took external examinations for a teaching certificate, and in January, 1880, he was appointed to teach arithmetic and geometry in the Borovskii County School, Kaluga Province.

While teaching in the district school, Tsiolkovskii began his first scientific research. His fundamental scientific work was closely related to three great scientific and technical problems, which he also approached as an inventor — an all-metal airship, an airplane, and a rocket for interplanetary flight.

Most of his work on all-metal airships was carried out between 1885 and 1892. He published the description and aerodynamic calculations of a streamlined airplane with light engine in 1894. After 1896 Tsiolkovskii systematically applied himself to the theory of rocket motion and proposed a series of designs for long-range rockets and rockets for interplanetary flight. In the last years of his life he did much fruitful work on the construction of a theory of jet airplane flight and produced his own design for a gas turbine engine. Tsiolkovskii's research on aerodynamics, rocketry, and dirigibles (the first three volumes of his collected works) have been published by the Academy of Sciences of the USSR.

In one of his autobiographical articles Tsiolkovskii wrote, "... In 1885, at the age of 28, I resolved to dedicate myself to aeronautics and to develop the theory of a metallic dirigible."** He turned his attention to the actual deficiencies of aerostats with casings of rubberized fabric. Such casings were not durable and soon wore out, and as a result of the penetrability of the fabric, the gas used to fill them (in those days, hydrogen) soon leaked out. The result of Tsiolkovskii's research was the bulky study "Teoriya i opyt aerostata" (Aerostats in Theory and Practice), in which he gave the scientific and technical foundation of the design of dirigibles with metal casings, together with sketches illustrating design details.

Tsiolkovskii's dirigible had the following characteristics: It was a dirigible of variable volume, which permitted maintenance of constant lift for different temperatures of the surrounding air and for different flight altitudes. Changes in volume were made possible by a special arrangement for contraction of the corrugated sides. The gas filling the dirigible could be heated by passing the engine exhaust gases through serpentines. The thin metal casing designed to increase durability was corrugated, and the corrugations were arranged perpendicular to the axis of the dirigible. Tsiolkovskii was the first to choose suitable geometrical

* Rynin, N.A. "K.E. Tsiolkovskii — ego zhizn , raboty i rakety." (K.E. Tsiolkovskii — His Life, Work, and Rockets), p. 10. Leningrad. 1931.

** Ibid., pp. 10–11.

forms for the dirigible and to calculate the strength of its thin casing, but his proposals went unrecognized. The official organization to deal with aeronautical matters in tsarist Russia, the Seventh Aeronautical Section of the Russian Engineering Society, found that a design for an all-metal dirigible capable of changing its volume could have no practical significance and that dirigibles "will eternally be the playthings of the wind." The author was therefore denied a subsidy even for the construction of a model. Tsiolkovskii's application to the General Staff of the Russian Army was equally unsuccessful. His published paper "Metal Dirigibles" (1892) received a few sympathetic reviews, and that was the end of the matter.

Tsiolkovskii also had the advanced idea of building an all-metal airplane. In an article of 1894, "The Airplane, a Birdlike (Aeronautical) Flying Machine,"* he gave a description and sketches of a monoplane whose external appearance and aerodynamic structure anticipate the aircraft designs worked out by aviation engineers only 15 to 18 years later.

Tsiolkovskii's airplane had wings of wide profile, with a rounded leading edge, and a streamlined fuselage. To resolve the aerodynamic questions arising in the determination of the airplane's flight characteristics, Tsiolkovskii built a free-flight wind tunnel and developed appropriate methods of aerodynamic experiment. Later (1900–1901), with a subsidy from the Academy of Sciences, he succeeded in blasting through some very simple models and determined the resistance coefficients of a sphere, a plane disk, a cylinder, a cone, and other solids.

Tsiolkovskii also foresaw the significance of internal combustion gasoline engines for the development of aviation. He wrote: "I have theoretical grounds for believing in the possibility of constructing exceptionally light and at the same time powerful gasoline or oil engines that fully satisfy the requirements of flight."** This airplane design, however, also was ignored by official Russian science. Tsiolkovskii had no means, and not even any moral support, for further research on airplanes.

He foresaw the significance of wind tunnels, and of systematic wind tunnel experiments to determine the influence of an airstream upon solids moving in it. He wrote, "How important it is to formulate the laws of resistance and friction as precisely as possible! What extensive application they have to the theory of dirigibles and airplanes! . . . We shall look forward to the establishment of these laws, and do whatever we can to promote the performance of experiments necessary for this purpose."† Konstantin Eduardovich carried out more than 1000 aerodynamical experiments for subsonic velocities, and succeeded in deriving the coefficient of friction from Reynolds number.

With some bitterness it must be added that the majority of Tsiolkovskii's discoveries in experimental aerodynamics were not published in prerevolutionary Russia, and as a result many of his deductions about the laws of air resistance had to be made a second time in the twentieth century by others.

Tsiolkovskii began his independent scientific work under very peculiar conditions. From any doctrinaire viewpoint it was altogether impossible for him to have any creative scientific activity. One need only imagine the quiet provincial town of Borovsk, far removed from the nation's highways, in the 1880's. There were neither libraries nor scientific journals, and

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.1, pp.40–73. Moskva. 1951.
** Ibid., p.70.
† Ibid., p.120.

newspapers came a week late. Tsiolkovskii was a teacher in a district school comprising two classes, whose physics and mathematics curriculum consisted of only the most elementary facts. The interests of his colleagues did not rise above the discussion of purely methodological questions. In spite of all this, Tsiolkovskii did the incredible! Making use of each comment on the new questions of science in the textbooks, and his own store of observations made in Moscow, and consequently working out the methods he would adopt for the independent proof and investigation of what was already known, he began to be aware of new and urgent scientific problems. Tsiolkovskii could not use printed literature to verify the ideas that occurred to him — there simply was none in Borovsk — and he carried out all his research from the beginning to the logical conclusion independently, in the full confidence that his idea was new and had not been studied by anybody else. In the case of success, his work was written up and forwarded to the capital to be judged by the appropriate officials.

"At first I discovered what had long been known, then what had not been known so long, and finally completely new things," Tsiolkovskii wrote in his autobiography.* The concurrence between his own findings and those of other scientists only convinced him of his own powers and talent.

From his earliest papers it is evident that Konstantin Eduardovich had an original mind, capable of selecting topics for consideration and finding solutions that opened new paths in science. His work was characterized by the sharp and lucid formulation of scientific problems. For the popularization of his ideas he usually resorted to colorful examples that convincingly revealed the essence of the matter, and his proofs were demonstrated by the simplest mathematical means. The results he obtained, and their consequences, were subjected to a thorough analysis. Behind his theoretical calculations Tsiolkovskii could perceive the authentic pulsating life of engineering, the struggle between dying, dogmatic academic schools and new ideas. He was capable of working persistently and unremittingly for the victory of the new, under conditions as little conducive as possible to creative work. His extreme independence and originality in scientific research sometimes bordered on disregard of generally accepted, reasonable norms, but he was capable of carefully analyzing the critical arguments of those who attacked his results, and vindicating his own scientific convictions. Tsiolkovskii was a man of great principle in his creative work, and his capacity for the independent investigation of scientific problems is a splendid example for all beginners.

He contributed much to the fundamental theory of rocket motion, and was one of the first in scientific history to formulate and study straight-line rocket flight, taking the general laws of theoretical mechanics as a starting point. Tsiolkovskii realized as early as 1883 that motion could be imparted by the reaction of ejected particles, but he did not construct a mathematically rigorous theory of jet propulsion until the end of the nineteenth century.**

In one of his papers Tsiolkovskii wrote: "For a long time I viewed rockets like everyone else — from the point of view of diversion and minor applications. I don't clearly remember how I first got the idea of performing calculations on rockets; I have the impression that the first seeds —

* Aeroflot (Soviet Airways) volume dedicated to K.E. Tsiolkovskii, p.45. 1939.

** Tsiolkovskii obtained the fundamental equation of rocket motion in May, 1897, independently of I.V. Meshcherskii's paper "Dinamika tochki peremennoi massy" (The Dynamics of a Point of Variable Mass), published in Petersburg at the end of 1897.

ideas — were planted in my mind by Jules Verne's well-known fantasy, which set my brain to work along now familiar lines. First desires appeared, and they in turn gave rise to mental activity. . . The old sheet with the definitive formulas dealing with jets is dated 25 August, 1898, but the preceding makes it evident that I got interested in the theory of rockets earlier, in 1896.

". . . I never claimed to give a full solution of the problem. The first inevitable progression of concept, imagination, and story is followed by scientific calculation, and thought is ultimately crowned by accomplishment. My work on space travel belongs to the middle phase of creation. I understand better than anyone else the abyss that separates an idea from its realization, since in the course of my life, I have not only thought and calculated, but have also completed projects, working with my hands. It is impossible, however, for there to be no idea: thought must precede execution, and imagination, precise calculation."*

The study of jet aircraft motion presents formidable difficulties, since the weight of any jet craft changes appreciably during its motion. There are single-stage rockets whose weight diminishes during the period of the engine's operation to some 10% of its original magnitude. This weight change during flight rules out the direct application of the formulas and conclusions of classical mechanics, which are the basis for calculation of the motion of solids of constant weight.

In engineering problems dealing with the motion of solids of variable weight, such as airplanes with large fuel supplies, it was usually supposed that their trajectory could be divided into parts, over each of which the weight of the moving body might be regarded as constant. In this way the difficult problem of the motion of solids of variable mass was transformed into the simpler and previously studied problem of the motion of solids of constant mass. Tsiolkovskii set study of straight-line flight of rockets, considered as bodies of variable mass, on firm scientific ground. The theory of rocket flight is now called rocket dynamics. Tsiolkovskii laid the foundation of modern rocket dynamics.

His published papers on rocket dynamics make it possible to follow the successive development of his ideas in this new field. Among the questions he considered and resolved are the following:

What are the fundamental laws governing the motion of solids of variable mass? How can the velocity of jet aircraft be calculated? How can the peak altitude of a vertically launched rocket be found? How can a jet craft get beyond the limits of the atmosphere, and penetrate the "armor" of gravity?

From our viewpoint, the most valuable of Tsiolkovskii's contributions to rocket theory is the addition of a new section to Newton's classical mechanics — the mechanics of solids of variable mass. The problem Tsiolkovskii set himself was no less than to subject to the human intellect a great new group of phenomena, to explain what many had seen, but not understood, and to give mankind a powerful new weapon for new engineering developments. All of his research talent, creative originality, unusual

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, pp.101, 180. 1954.

flights of fantasy, and his particular strength and productivity appeared in his work on jet propulsion. He predicted the course of development of jet aircraft decades ahead, and studied the changes which the ordinary flare rocket would have to undergo in order to become a powerful weapon of progress in a new field of knowledge.

In one of his papers (1911), Tsiolkovskii expressed a profound thought about the very simple applications of rockets that had long been known: "What we usually observe of jet propulsion on earth is so pitiable as to encourage nobody to dreams and research. Only intellect and science could indicate the transformation of these phenomena into what is grandiose and almost inscrutable to the senses."*

The rockets Tsiolkovskii proposed were not designed with the sketches and technical drafting familiar to the modern rocket engineer. In the main they were demands for new ideas. Tsiolkovskii devoted most of his attention to scientific calculations which demonstrated the feasibility of his projects. These calculations could not be satisfied by the well-known formulas of classical Newtonian mechanics, but required the creation of a new science — rocket dynamics.

In his papers Tsiolkovskii gave a rigorous mathematical solution of the most important problems of the rocket dynamics of straight-line flight. Tsiolkovskii solved the first problem of rocket dynamics by assuming the absence of gravity and aerodynamic forces, and gave a formula for calculation of rocket velocity which showed the theoretical possibility of jet propulsion without taking into account the losses occasioned by the forces of gravity and drag.

In the second problem of rocket dynamics Tsiolkovskii investigated the straight-line vertical climb of a rocket, taking into account the force of gravity. Assuming the boost phase trajectory to be small in comparison with the earth's radius, he regarded the gravity field as uniform, and the acceleration due to gravity as constant and equal to its value on the surface of the earth. The formulas obtained by Tsiolkovskii are still widely used in rocket design.

Detailed study of straight-line rocket flight and calculations of exhaust velocities for different propellants brought Tsiolkovskii to the conclusion that the attainment of high velocities, in the case of single-stage rockets, was a very difficult engineering problem. In 1929 Tsiolkovskii suggested an original means of communicating escape velocity to the payload, with familiar, readily available propellants. He worked out a theory of multistage rockets or rocket trains. The descriptions given in his papers show that he proposed the construction of two types of rocket trains.

The first type was like a railroad train, when the locomotive pushes the train from behind. A train of three rockets, for example, consecutively coupled together, would first be moved by the lowest (tail) rocket. When the fuel of the tail rocket was exhausted, it would be jettisoned and fall to the earth. The engine of the second (middle) rocket would thereupon begin to function, and its thrust would propel the two remaining rockets. When the fuel of the second rocket was fully consumed, it would also be jettisoned, and the engine of the last rocket would be started. This rocket would be

* Tsiolkovskii, K.E. "Trudy po raketnoi tekhnike" (Papers on Rocketry), p. 60, Moskva, 1947.

able to reach a much higher velocity than a single rocket, since the two rockets discarded in flight would already have imparted some velocity to it.

Tsiolkovskii called the second type of rocket train (or step-rocket) a rocket squadron. Four connected parallel rockets, for example, were launched together. When each of the four had used half of its fuel supply, two of the rockets (for example, one on the right and one on the left) poured their remaining fuel into the half-empty tanks of the other two rockets, and were then jettisoned, leaving two rockets to continue the flight. When these consumed half of their fuel, one of the rockets transferred its remaining fuel to the other, which was intended to complete the journey.

If the force of air resistance is neglected, all the flight characteristics of rocket trains of both types can be found by the successive application of Tsiolkovskii's formulas.

Finding a reasonable rocket train design is one of the most pressing problems at the present day, and many scientific journals publish articles by scientists and engineers, devoted to the development of Tsiolkovskii's far-reaching schemes. He was the first to establish scientifically the possibility of using multistage rockets to attain escape velocity and he gave a rigorous mathematical proof of the feasibility of space travel. The experience of the past few years has fully substantiated his ideas.

Given the launching weight of the rocket train, Tsiolkovskii's theory permits determination of the optimum distribution of weight in its separate stages, so as to secure maximum velocity for the final stage (payload).

The case of a rocket train in which equal increments of velocity are obtained from each stage is of special interest. In this case the weights of the successive rockets in the train will increase in geometrical progression. After Tsiolkovskii's death it was demonstrated with mathematical rigor that this was the optimum multistage rocket design and would give maximum altitude (or range). Taking into account that with the increase of the launching weight of the rocket, the reactive force and the force of gravity increase as the cube of the object's characteristic size, while the resistance increases only as the square, a sufficiently accurate determination of the flight characteristics of big rockets may be obtained by consideration only of the force of gravity and the reactive force. Nowadays, therefore, Tsiolkovskii's solution of the second problem of rocket dynamics has acquired special significance.

The rocket dynamical problems considered by Tsiolkovskii were extremely simple, since they took the trajectory of the rocket's center of gravity to be a straight line, and altogether disregarded the influence of control systems. Most modern rockets and space ships have, beyond flight control systems, remote control systems whose influence on flight characteristics is decisive. In the most general case a rocket flight control system consists of the following elements:

a) remote control apparatus and systems, which work out flight control orders and transmit them through radio links. These orders alter procedures in the control equipment on board the rocket (for example, they change the position of the control vane or spoilers, switch on the jet engines, alter the gear ratios through the automatic pilot channels, etc., so as to assure homing of the rocket on its target.

b) apparatus and systems for stabilization of the rocket and automatic fulfilment, in predetermined sequence, of the orders received from the

radio flight control. The automatic pilot, which confers flight stability and influences the controls (vanes, ailerons, spoilers, and steering engines) is the principal instrument on board the rocket;

c) telecontrol apparatus and systems, which give information about the locations of target and rocket, and about the functioning of the rocket's fundamental assemblies.

The interaction of the major elements of a control system can be schematically pictured by considering the flight of a surface-to-air missile, intended to hit an enemy airplane. The group of telecontrol aids (in the first phase, means of target acquisition) fixes the present-position data of the target on the command post. If the target enters its combat zone, the rocket is launched, and thereafter the telecontrol aids simultaneously give the present-position data of target and rocket, making it possible to know their relative positions. If these do not correspond with what is required by the assumed homing method (which is usually chosen from the kinematic engagement conditions of target and rocket), remote control devices work out the corresponding orders, whose function is to bring the rocket on to a homing trajectory and assure a kill, and communicate them to the systems on board.

The telecontrol, remote control, and stabilization procedures which form part of the group of rocket flight control devices are determined by exceedingly complicated differential and algebraic equations. The study of the processes described by such equations is one of the difficult tasks of the theory of automatic control.

The most important characteristic elements of control systems are the stability of the system (or of parts of the system), and the "reactions" of the system to external influences. It should be noted that external influences on some of the elements of a control system can be mathematically represented by random functions of time and in this case the study of the system's "reaction" requires thorough knowledge of the theory of stochastic processes.

The more complicated motion of modern guided rockets has naturally required development of Tsiolkovskii's ideas, but subsequent progress in the methods of rocket dynamics shows the profundity and greatness of his research, which correctly reflected the chief dynamic properties of rocket motion.

In the last years of his life Tsiolkovskii worked a great deal on the construction of a theory of jet airplane flight. In his article "Reaktivnyi aeroplan" (Jet Airplanes), of 1930, he elucidated in detail the advantages and deficiencies of jet airplanes in comparison with propeller aircraft. Discussing the high fuel consumption of jet aircraft as one of their major drawbacks, Tsiolkovskii wrote: ". . . Our jet airplane is five times as disadvantageous as a conventional airplane, but it flies twice as fast where the atmospheric density is one-fourth as great. There it will be only 2 1/2 times as disadvantageous. Still higher, where the air is 1/25 as dense, it flies 5 times faster and is therefore as economical in its use of energy as a propeller aircraft. At an altitude where the medium is 1/100 as dense, its velocity is 10 times as great, and it will be twice as advantageous as a conventional airplane."*

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, pp.337-338.

Tsiolkovskii concluded this article with some remarkable words illustrating his profound understanding of the laws of technical development: "The era of propeller airplanes must be followed by an era of jet or stratosphere airplanes."* It should be noted that these lines were written ten years before the first jet airplane, constructed in the Soviet Union under the direction of V. F. Bolkhovitinov, took to the air.

In the articles "Raketoplan" (Rocket-propelled Aircraft) and "Stratoplan polureaktivnyi" (Semijet Stratospheric Aircraft) Tsiolkovskii gave the theory of liquid-propellant jet aircraft motion and developed in detail the idea of the turbo-prop airplane.

The fundamental directions of Tsiolkovskii's theoretical research on rocket dynamics have been briefly indicated. His merit lies in the fact that he subjected completely new effects to precise mathematical analysis and engineering design. Tsiolkovskii's rigorous mathematical analysis of the problems of rocketry revealed the fundamental laws of rocket motion and made it possible to evaluate quantitatively the degree of perfection of practicable rocket designs.

Rocket dynamics is a science of the twentieth century. The basic principles of this science are to a considerable extent the creation of K. E. Tsiolkovskii.

Tsiolkovskii's accounts of his research on the theory of jet propulsion were written with wide scope and unusual imagination. In all of his work on rocketry his basic striving was to work out scientifically the problems of space travel.

The noble and humane goal of Konstantin Eduardovich's research was to give the world a means of conquering the space about the sun. He did not write a work about the military applications of rockets, but directed all of his efforts towards the good of mankind, the benefit of science, and the dissemination of knowledge of the laws of nature.

"... As a student of the atmosphere I propose a jet machine, that is, a sort of rocket, but a rocket constructed in a special way. This thought is not new, but the calculations relative to it give such remarkable results that it would be intolerable to keep silent about them. This work of mine is far from examining all sides of the question and does not at all solve it from the practical point of view, but far in the future it is possible to see, through the mist of distance, things so seductive and important that now they are hardly dreamed of."**

The question of the practicability of space travel interested Tsiolkovskii from the very beginning of his independent scientific research. His naive youthful dreams, the systematic analysis of the simplest mechanical phenomena in a space with no forces acting (in free space, to use Tsiolkovskii's terminology), then the thorough mathematical development of the idea of jet propulsion with the detailed quantitative analysis of straight-line motion, and finally the theory of rocket flight, of an immense rocket capable of transporting people into outer space – these are the successive stages of

* Ibid., p.338.

** Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.73.

Tsiolkovskii's creative research, which prepared the soil for the sprouting of a new scientific discipline: cosmonautics or astronautics.

"A space vehicle must be similar to a rocket," said Tsiolkovskii. Indeed, "All vehicles have one and the same basic means of operation: they push a mass away in one direction and are thereby themselves moved in the opposite direction. A steamship pushes away water, a dirigible or an airplane, air, a man or horse, the earth. . ."* The rocket contained within itself the substance to be ejected. The propellant comprised a fuel and an oxidant, and no external means or base was required to impart motion to the rocket. In a vacuum a rocket accelerates more rapidly, since there is no air resistance to be overcome. "Evidently any device for motion in a vacuum must be similar to a rocket, that is, must contain not only energy, but a reference mass, within itself."** The reactive force developed by the jet engine could be used for any movement in space. A rocket would be in a position to "leave the earth behind, wander among the planets, among the stars, visit the planets and their satellites, rings and other heavenly bodies, and return to the earth, if only it had sufficient energetic explosive."†

The motion of a rocket in outer space is determined by the laws of celestial mechanics, since a space rocket is a new planet. Since the dense layers of planetary atmospheres are concentrated at low altitudes (by comparison with the radius of the corresponding planet), in the majority of cases only the force of gravity need be taken into account in studying rocket motion within the limits of the solar system (flights from one planet to another). To investigate the motion of artificial earth satellites and rockets intended to reach (or circle) the moon, in a number of cases only the earth's gravity field need be considered.

Tsiolkovskii's idea of preserving living things and men from great g-loads ("reinforced gravity," as he called it) by immersing them in a liquid of equal density was of great interest for future space flights. This idea is first encountered in Tsiolkovskii's writings in 1891.†† A short description of a simple experiment will convincingly demonstrate the correctness of Tsiolkovskii's proposal for uniform bodies (bodies of equal density). Take a delicate wax figure that can scarcely support its own weight. Pour into a strong vessel a liquid of the same density as the wax, and immerse the figure in this liquid. Then by means of a centrifuge apply g-loads greatly exceeding the force of gravity. If the vessel is insufficiently strong it will break, but the wax figure in the liquid will be preserved whole. "Nature, immersing in liquid the embryos of living things, their brains, and other weak parts, has long made use of this method," wrote Tsiolkovskii. "Thus she preserves them from every sort of injury. Man, however, has so far made little use of this idea."‡

It should be noted that for nonuniform solids (of different densities), the effect of g-loads will be felt even in the case of immersion in a liquid. For example, if lead pellets are enclosed in the wax figure, great g-loads

* Ibid., p. 181.

** Ibid.

† Ibid.

†† Tsiolkovskii, K.E. "Kak predokhranit' khrupkie i nezhnye veshchi ot tolchkov i udarov" (How to Protect Fragile and Delicate Things from Shocks and Bumps).— Papers of the Division of Physical Sciences, Society of Natural Science Amateurs, Vol. IV, No. 2, pp. 17–18. 1891.

‡ Ibid.

will expel them into the fluid. There is no doubt, however, that in a liquid man can withstand greater forces than, for example, in a special armchair.

How would mankind profit from possession of the abysses of outer space? According to Tsiolkovskii, the most important gain would be in the form of solar energy, of which, according to his estimate, only one two-billionth is now received by the earth. In "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Outer Space by Jet Machines) he wrote:

"Further exploitation of solar energy would probably take place as follows.

"Mankind will send missiles to one of the asteroids, chosen as a base for its initial projects, and will use its material, taking it completely apart, for its own constructions, which will constitute the first solar ring. This ring, full of intelligent creatures, will consist of movable parts and will resemble the rings of Saturn.

"By disassembling and using other such tiny asteroids, this sensible method can form another series of rings, somewhere between the orbits of Mars and Jupiter, for the attainment of its goals in open space, i.e., space free from asteroids."*

Space travel would infinitely expand the possibilities for scientific research. Nature's great laboratory would be more accessible, and an interpretation of the phenomena taking place in it would be simpler and more trustworthy.

Tsiolkovskii also addressed himself to skeptics:

"... There was a time, not at all long ago, when the idea that it might be possible to know the composition of the heavenly bodies seemed folly, even to eminent scientists and thinkers. That time is now past. But I think that the notion of closer, direct study of the universe will seem even stranger at the present day. To set foot on the soil of the asteroids, pick up a moonstone with one's hand, build stations moving through the ether, form living rings around the earth, moon, and sun, look upon Mars from a distance of a few dozen versts, land upon its satellites or even on the surface of the planet itself – all this may well seem more extravagant! The first use of jet craft, however, will open a new era in astronomy – an era of more intent study of the heavens. The great, frightening force of gravity will scare us no more than it should! A cannon-ball, moving with a velocity of 2 km/sec, seems nothing wonderful to us. Why should a missile, flying at 16 km/sec and eternally traveling away from the solar system into the interminable universe, overcoming the gravity of earth and sun and all its system, fill us with awe! There is such an abyss between the numbers 2 and 16! and yet one is only 8 times the other.

"If one unit of velocity is possible, why should a velocity of 8 units be impossible? Doesn't everything progress and move forward, and moreover, with startling rapidity?

"Long ago our grandmothers found a velocity of 10 versts on the earth puzzling and hard to believe, and now automobiles move at 100 to 200 versts per hour, that is, 20 times faster than in Newton's time. In the past it seemed strange to think of using forces other than muscle, wind, and water! One might never finish speaking on this subject."**

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.127. 1954.

** Rynin, N.A. "K.E. Tsiolkovskii – ego zhizn', raboty i rakety" (K.E. Tsiolkovskii – His Life, Work, and Rockets), p.14.

Whoever studies Tsiolkovskii's writings and compares his research with that done abroad subsequently, will readily agree that the theoretical foundations for the calculation of the motion of all jet aircraft were laid in Russia, and that Tsiolkovskii, the pioneer in these new scientific disciplines, gave to rocket dynamics and cosmonautics the unusual scope and depth of inference that are characteristic of the great works of the human mind.

In all of Tsiolkovskii's articles on rocketry the independence and originality of his research work is evident: his language is easily understood and his mathematical calculations serve only to support logical deductions and conclusions, nowhere obscuring his clearly formulated scientific ideas. As in all immortal creative work, whose greatness and progressivity appear only in the course of time, the perceptive reader will note in Tsiolkovskii's writings the remarkable simplicity of judgment, and penetration into the order of nature, which are characteristic of classic works.

Nevertheless, those of Tsiolkovskii's papers written before the October Revolution suffered the fate of many discoveries and inventions made in Tsarist Russia. Far ahead of their time, they received no recognition from the officially appointed representatives of science.

Tsiolkovskii wrote bitterly, "It is hard to work for many years in solitude, in unfavorable conditions, and with neither encouragement nor support from any quarter."*

After the Revolution the circumstances of Konstantin Eduardovich's life and work were completely different. In 1919 he was made a member of the Socialist Academy. A personal pension was assigned to him by a decision of the Council of the People's Commissars. The Commission for Improvement of the Lot of Scientists (TsEKUBU) accepted responsibility for Tsiolkovskii and guaranteed him satisfactory living conditions in the difficult and tense period of the civil war.

Governmental and social organizations began to assist Tsiolkovskii in the publication of his works. Between 1917 and 1935 four times as many of his articles, pamphlets, and books were published, as in the entire preceding period of his active life.

Between 1925 and 1932 about 60 works of Tsiolkovskii's dealing with rocket dynamics, physics, astronomy, mechanics, and philosophy were published. The government's constant interest in his scientific research facilitated the wide diffusion and recognition of his work, and Tsiolkovskii became known to the whole world of science and engineering. Translations of his articles began to appear in foreign technical journals. The world's greatest rocket theoreticians studied his research, and Tsiolkovskii came to be recognized as the founder of a new path in engineering – rocket engineering. Special discussions were devoted to Tsiolkovskii's equations and formulas, and his work on jet propulsion and space travel found many talented inheritors. Groups and societies for studying the possibility of space travel were founded in a number of countries (Germany, England, France, America), and experiment and construction were begun. The idea of interplanetary travel was a creative stimulus uniting considerable groups of scientists and inventors. The colossal progress in rocketry, of which we are the witnesses, was initiated more than 60 years ago by K. E. Tsiolkovskii. To a great extent

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.140.

Tsiolkovskii's research, and that of his many followers in the thirties and forties, prepared the ground for this progress.

The October Revolution inspired the sixty year-old Tsiolkovskii with new creative daring, and his gifts appeared in their full strength and glory. He stood before his contemporaries as a pioneer in a new field of human knowledge, a new science, a new branch of industry. Many before Tsiolkovskii had observed rocket flight, and history tells us that the first flares were built in China more than 2000 years ago. No builder of rockets, however, and none of the millions of people who watched fireworks, came to found a new science — the theory of rocket flight. Furthermore, solid-propellant rockets were the object of attention of a considerable circle of military specialists throughout almost all the nineteenth century, and yet no theory of rocket motion existed before Tsiolkovskii's work.

As Galileo saw in the everyday phenomenon, observed by everyone, of falling bodies, the laws of equally changing (equally accelerated and equally decelerated) motion lying behind it, the simple and adequate laws of the essence of these phenomena, so in the new field of rocket motion Tsiolkovskii discovered an order, and revealed the fundamental principles characterizing this class of motion. These laws are as simple and transparent as spring water. They cannot be avoided in the problems of rocket engineering, nor can they be consigned to oblivion. They can easily be scanned as the fundamentals of most contemporary work on theoretical rocket dynamics.

The greatness of Tsiolkovskii's gifts and his creative originality appeared to best advantage precisely here, where very many scientists saw nothing worthy of attention. The ability to comprehend the full importance of research on the flight of rockets as bodies of variable mass is, considering the level of Russia's economic and scientific development at the turn of the twentieth century, an outstanding phenomenon. Only a man of extraordinary gifts, with the penetration of genius, could have broadened knowledge of the objective laws of nature, extended new paths of research in an unknown field, and given results of classic clarity and simplicity.

The breadth of Tsiolkovskii's scientific outlook can be partially indicated by the titles of the articles he wrote between 1916 and 1930. Here, for example, are only a sixth of the papers he published during those years:

"Gore i genii" (Grief and Genius) (Kaluga, 1916, published by the author); "Vne Zemli" (Beyond the Earth) (a fantastic tale, partly published in the magazine "Priroda i lyudi" in 1918); "Monizm vselennoi" (The Monism of the Universe) (Kaluga, 1925); "Prichina kosmosa" (The Origin of the Cosmos) (Kaluga, 1925); "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Outer Space by Jet Machines) (Kaluga, 1926); "Moya pishushchaya mashinka" (My Typewriter) (Kaluga, 1928); "Um i strasti" (Intellect and the Passions) (Kaluga, 1928); "Rastenie budushchego" (Plant of the Future) (Kaluga, 1929); "Zvezdoplavatelyam" (To the Star Navigators) (Kaluga, 1930); "Reaktivnyi aeroplan" (Jet Airplanes) (Kaluga, 1930); "Ot samoleta k zvezdoletu" (From Airplane to Starplane) (Kaluga, 1930); "Nauchnaya etika" (Scientific Ethics) (Kaluga, 1930).

His years of successful work under the Soviet regime, and his observations of the development of science and engineering in the Soviet Union, convinced Konstantin Eduardovich of the complete feasibility of his fundamental ideas. During a radio transmission from Red Square on 1 May, 1933, Tsiolkovskii, in his quarters in Kaluga, was tuned in for a few minutes.

Here are a few thoughts expressed by Konstantin Eduardovich in his brief words of greeting to the entire Soviet people:

"Greetings!

"I picture to myself Red Square in the capital. Hundreds of steel dragonflies wave above the heads of the marching columns. Low flying dirigibles — the dream of my youth, the fulfillment of cherished imaginings, to some extent the result of my labors — go floating by. The air is thick with steel birds, and we have made that possible only now, when our party and government, all our industrious people, every worker of our Soviet Russia, have amicably applied themselves to the realization of mankind's most daring dream — conquest of the heights beyond the clouds. This is an unprecedented achievement! Nothing like it existed or could exist before. It is small wonder, therefore, that Soviet pilots have climbed higher than all others into the mysterious stratosphere. The world records of our parachutists and the records for flight duration and the numerous instances of the heroism of our glorious conquerors of the air are easily explained.

"Now, comrades, I am firmly convinced that my second dream — space travel — for which I have given the theoretical foundations, will be realized.

"I worked on jet engines for forty years and thought that travel to Mars would be possible only after many centuries. But times are changing. I believe that many of you will be witnesses of the first journey beyond the atmosphere. In the Soviet Union we have many young pilots — for I give the name to children who build model airplanes and fly gliders — youth in the air. We have tens of thousands of them. I place my most daring hopes in them. They will help to actualize my discoveries and will prepare the gifted builders of the first space vehicle.

"Heroes and dare-devils will lay the first airways: Earth to orbit of moon, Earth to orbit of Mars, and still farther; Moscow to the Moon, and Kaluga to Mars." *

Tsiolkovskii's papers on rocket dynamics and the theory of space travel were the first serious research on these subjects in all scientific and technical literature. In this research the mathematical formulas do not obscure the profound and clear ideas, originally and accurately formulated. More than half a century has passed since the publication of Tsiolkovskii's first articles on the theory of jet propulsion. The appearance of a stern and merciless judge — time — has served only to emphasize the greatness of our famous scientist's ideas. His work will promote new daring in Soviet science and engineering. The Soviet Union can well be proud of her gifted son, a true ornament of the human species, opener of new ways in science and industry.

He was a passionate dreamer. He meditated on the sources of the sun's colossal energy, on the laws of rocket motion, on the construction of all-metal dirigibles and airplanes, on new forms of polity, on artificial interplanetary islands, settled by the bold offspring of people who by their work had already converted our planet into a flowering garden, of a new international scientific language in place of medieval Latin, and of many other things.

Rigorous mathematical analysis, numbers, restrained these flights of fancy. The motto of Tsiolkovskii's research was scientific calculation, which always followed dreams, imaginings, and stories.

* Aeroflot (Soviet Airways) volume dedicated to K.E. Tsiolkovskii (1939), pp. 11-12.

He strove to show his contemporaries new unknown paths in scientific research, new undiscovered worlds, new human relationships, a different life. He aroused intellects and called upon them to create, awakening desires for reflection, search, and creation. His voice was powerful, not only when proved right, but even when in error. His passionate and ardent faith in the power of intellect, science, and man's indomitable striving for improvement were fascinating.

He learned as he worked. Often thorny paths led him to what had already been found by others, but he was irresistibly attracted by the process of intellectual creativity. The joy of the first discoverer kindled and fed his imagination.

Many scientists failed to understand him. He published his articles in journals which were not much read by working scientists, and was better known to engineers and inventors, people with a nose for the new and unexpected. In those days most scientists did not even consider the subject of Konstantin Eduardovich's research to exist. Rockets had been buried "by common consent" in the 1880's. To cold and lazy minds it seemed that Tsiolkovskii was writing about unrealizable things, already repudiated by the advance of history. The form and style of his articles often irritated pedants, who considered the Russianized terms used by Tsiolkovskii to record formulas familiar from his school years a whimsy of dying Slavophilism. They criticized the absence of citations from the published works of his precursors as arrogance and contempt for genius.

The unhappy fate of almost all of Tsiolkovskii's pre-revolutionary discoveries aroused a storm of protest in him. He mentally turned the pages of a great volume of the history of science and compared his own discoveries with those of the great men of natural science and engineering, finding not a few analogies. In the foreword to his paper "Raketa v kosmicheskoe prostranstvo" (Rocket to Outer Space) he wrote: "... Lamarck wrote a book in which he analyzed and demonstrated the development of creatures from the lowest organisms to man. The French Academy with the renowned Cuvier as its head derided the book and publicly called Lamarck a donkey. Galileo was tried and imprisoned and forced ignominiously to retract his teaching of the earth's rotation. Only by so doing was he saved from the stake. Kepler was imprisoned. Bruno was burned for teaching that there is a multiplicity of worlds. The French Academy rejected Darwin, and the Russian Academy, Mendeleev. Columbus, after discovering America, was put into chains. The derision of scientists led Mayer to the madhouse. The chemist Lavoisier was put to death... There is no counting those that have been burned and hanged for the sake of truth; history is full of such things. And why have academies, scientists, and professionals been condemned to play such a wretched role as extinguishers and even chastisers of truth?"*

After 1917 Tsiolkovskii wrote bitingly of the blindness of pre-revolutionary scientific officials to anything new, and of its fidelity to what was canonical and was becoming outmoded. He realized that he belonged in the first rank of pioneers in great discoveries and he wished to open the eyes of all to the riches daily standing before his intellectual glance.

The conditions under which Konstantin Eduardovich worked were frightful even by the standards of tsarist Russia. He had a miserable salary,

* Tsiolkovskii, K.E. "Raketa v kosmicheskoe prostranstvo" (Rockets into Space), Kaluga, 1924. p.IV.

a large family, and a dark and uncomfortable apartment. Fires and floods repeatedly destroyed almost all of his manuscripts and rough draft calculations. He had no access to needed scientific literature, either in Borovsk or Kaluga. He could only dream about journals and current scientific periodicals. The coarse mockery of the philistines of provincial Russia was his only encouragement. The systematic cavilling of his fellow-teachers, ready to quarrel with the least methodological innovation in teaching, hardly contributed to his productivity. All were dissatisfied with the fact that Tsiolkovskii, a poor man, printed scientific articles with his own means and distributed them gratis. His deafness seems to have saved the greatness of this man from the mire of the "loyal and thick-skinned" petty bourgeoisie. In pre-revolutionary Kaluga there were no more than ten people that understood the content of Tsiolkovskii's scientific articles.

In 1926 he wrote to Professor N. A. Rynin characterizing the pre-revolutionary conditions of his scientific work: "There were then not many books in general, and I especially had few. I therefore had to think independently and often followed false trails. Frequently I discovered what had long been known. I learned through my creative work, though often unsuccessfully and with delays. Consequently I am accustomed to examine everything critically. I think, however, that originality was a part of my nature. Deafness and involuntary removal from society only enhanced my independence."*

All of the subtle mathematical techniques of the twentieth century were not available to him, and the mathematical apparatus he employed in his papers was very simple and comprehensible to anyone who had completed a normal university course in higher mathematics. He saw the essence of many phenomena, however, and was not afraid to make mistakes in trying to obtain new laws.

Mathematical technique and symbolism is something like musical notation or the rules of versification. It is possible to give a splendid explanation of the chords and sequences in the minuets of Haydn and Mozart, and yet be incapable of writing original music. It is possible to discuss in various ways the structure of the verses of Pushkin, Blok, and Esenin, but with the sad conviction that such knowledge contains no whit of true poetry. One can reproduce by memory all of the powerful mathematical discoveries made up to the present day without being able to apply them to the simplest problem. There is a logically elusive leap in our consciousness, when we begin to pass from the known to the unknown, when what has been discovered by the great figures of the past does not interfere with the vision of new things, as yet undiscovered, and still undreamed of, in the world.

The most difficult thing in scientific training is to avoid, while still a student, falling under the fascination of the well-known, and often more powerful, minds of the past, and instead to preserve one's own creative understanding of reality.

Tsiolkovskii did not like to examine the work of his precursors in detail. Usually he was quick to grasp the "pearl" of what was new in any scientific paper, and found the proofs himself. Results well known in science were therefore given by Tsiolkovskii in his own unexpected, fresh, original way. He was able to dream and to see "seductive, important prospects" in rocketry, his formulations and conclusions show sagacity and precision,

* Rynin, N. A. "K. E. Tsiolkovskii — ego zhizn', raboty i rakety" (K. E. Tsiolkovskii — His Life, Work, and Rockets), p. 10.

and his presentation of new problems moved his readers and stimulated their intellects.

Mathematical techniques can be taught. Becoming familiar with what others have done is only a matter of patience. Creation of what is great, however, cannot be taught. The value of the finest scientific school is in its ability to awaken and perfect the gifts of nature, if they are great, but no scientific school can alter inadequate capacities or develop acumen and intelligence, if they are not already there.

Tsiolkovskii possessed outstanding capacities, a penetrating glance for natural phenomena, and enormous will-power and patience. His faith in the new directions taken by the technical development of society, even when they were also perceptible to his contemporaries, was a characteristic trait of this great researcher. His accurate foresight into the course of progress and his full understanding of the aim of social development gave him a great faith in the conquest of the new ideas which he at first expressed partially in a logically imperfect form. In his familiar article "O roli lichnosti v istorii" (The Role of Personality in History), G. V. Plekhanov showed that great men should properly be called b e g i n n e r s . "This is a very apt term. The great man is a beginner precisely because he sees farther than others and desires more strongly then they. He resolves scientific problems posed in turn for the earlier intellectual development of society; he indicates new general needs created by the earlier development of social relations."

K. E. Tsiolkovskii was just such a great beginner.

N66 37131

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K. E. TSIOLKOVSKII — FOUNDER OF THE THEORY OF MULTISTAGE ROCKETS

(K. E. Tsiolkovskii — osnovopolozhnik teorii mnogostupenchatykh raket)

In the present work, which has the character of a historico-critical study, the development of the idea of staged rockets through the work of Soviet scientists in the 1930's is considered. It is well known, of course, that R. Goddard* in America, and H. Oberth, ** in Germany, were also concerned with the question of staged rockets.

In its original form the idea of staged rockets was expressed by the renowned Soviet space flight specialists F. A. Tsander and Yu. V. Kondratyuk. The theory of multistage rockets, however, was more thoroughly studied by K. E. Tsiolkovskii, who can rightly be regarded as its founder.

A more advanced stage in the development of Tsiolkovskii's multistage rockets came when scientific and technical development were such as to permit realization of Tsander's and Kondratyuk's ideas about the full utilization of the "proportional passive," that is, of the temporarily worthless used up and jettisoned structural parts of the multistage rocket.

In order to show more fully the role and significance of Tsiolkovskii's fundamental ideas and proposals in the development of multistage rockets, it has been thought expedient to present them in terms of the methods and suggestions of contemporary rocket dynamics. The four types of multistage rockets designed by Tsiolkovskii (and designated by him A, B, C, and D), both in special forms and in the form of the so-called "generalized Tsiolkovskii rockets," will be considered. The final section, in which Tsiolkovskii's four types of multistage rockets (A, B, C, and D) will be examined, will thus be preceded by two sections, one of which will be devoted to Tsiolkovskii's fundamental theory of simple rocket motion and its elementary applications, and the other, to the basic theory of generalized Tsiolkovskii multistage rockets.

THE CLASSICAL SOVIET COSMONAUTICS OF MULTISTAGE ROCKETS

The first students of cosmic flight, Tsiolkovskii, Tsander, and Kondratyuk, right at the outset of their work on cosmonautics, came to the

* Goddard, R. A Method of Reaching Extreme Altitudes. — Smithsonian Misc. Col., Vol. 71, No. 2. 1919.
** Oberth, H. Die Rakete zu den Planetenräumen. München. 1923.

important conclusion that a simple (single) rocket, operating on ordinary chemical fuel, could not possibly attain even circular velocity (8000 m/sec).

This followed directly from Tsiolkovskii's formula for ideal rocket velocity, published in 1903 in "Issledovanie mirovykh prostranstv reaktivnymi priborami,"*

$$V = c \ln(1 + z), \qquad (1)$$

where c is the relative exhaust velocity of the combustion products, and z, Tsiolkovskii's number, characterizing the relative fuel supply. Formula (1) applies for rocket flight in "free space," i.e., in an imaginary space with neither gravity nor resistance. For given values of c and z the velocity of the rocket in such an ideal space will be greater than any of its possible values under actually existing conditions, and V in (1) is therefore termed "ideal" velocity.

Inserting into (1) the maximum actually attainable values of c and z (ordinary "chemical" rockets, and not ionic or nuclear ones, are being considered),

$$c = 5000 \text{ m/sec}, \quad z = 4,$$

a value of about 8000 m/sec is obtained for the ideal velocity of the rocket. This is the lowest boundary of escape velocities, the so-called circular velocity, which would permit an artificial satellite to orbit the earth. Since gravity and atmospheric resistance make the actually attainable velocity considerably lower than the ideal figure given by (1), it is clear that a simple "chemical" rocket cannot reach even circular velocity, let alone the velocities required for flights from the earth to the nearest celestial bodies (the moon, Mars, etc.).

In his paper "Kosmicheskie raketnye poezda" (Cosmic Rocket Trains) Tsiolkovskii wrote: "A single rocket, in order to reach escape velocity, must have a very large fuel supply. For example, to reach circular velocity (8 km/sec), the weight of fuel must be at least 4 times as great as the weight of the rocket with all of its remaining contents. This impedes the construction of jet craft."** Tsander† and Kondratyuk†† came to the same conclusion.

The difficulties encountered in converting a rocket using ordinary chemical fuel to a space rocket could of course be obviated by the possible use of more efficient sources of energy (as in atomic engines and photon rockets), but even at present the practical resolution of the problem of applying nuclear energy in rocketry seems to lie in the quite distant future, although Tsiolkovskii envisaged such a possibility. He wrote, "I considered that radium, continually decaying into a more elementary material, emits particles of various masses, moving with incredibly high velocity, not much below the velocity of light... These velocities are 6000 to 50,000 times greater than the velocity of the gases leaving the nozzle of our jet pipe."‡

Tsiolkovskii, Tsander, and Kondratyuk could therefore seek means of overcoming the indicated difficulties only through improvement of ordinary

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.105. 1954.

** Ibid., p.299.

† Tsander, F.A. "Problema poleta pri pomoshchi reaktivnykh apparatov" (The Problem of Flight by Means of Jet Craft), p.223. Moskva. 1947.

†† Kondratyuk, Yu.V. "Zavoevanie mezhplanetnykh prostranstv" (The Conquest of Interplanetary Space), p.21. Moskva. 1947.

‡ Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.136.

"chemical" rockets. Insofar as the parameter c in (1) has quite a low limit for ordinary chemical sources of energy ($c \leqslant 6000$ m/sec), the only remaining way was to seek latent possibilities of considerably increasing the value of the parameter z.

A rocket comprises three types of mass, which have completely different designations: the mass of the propellant $m^{т}$, which is the source of energy for propulsion of the rocket; the payload m^{p}, that is, the mass which the rocket is intended to transport (an explosive charge or a crew, together with the means of their subsistence, etc.); and the dry mass m^{c}, the full starting mass of the rocket less the masses of payload and propellant. The dry mass consequently comprises the rocket main body, the engines, pumps for displacing the propellant into the combustion chamber, fuel tanks, steering mechanisms and controls for maintenance of predetermined flight conditions, etc. Then

$$m^{0}=m^{т}+m^{p}+m^{c},$$

where m^{0} is the full starting mass.

Kondratyuk called the payload m^{p} the "absolute passive,"* since it is a fixed quantity, according to which $m^{т}$ and m^{c} are calculated. The most perfect rocket design would be one which at every moment maintained a proportionality between the dry mass and the propellant mass. In a simple rocket, however, this could not be achieved, for it is impossible to conceive of continually shrinking engines, body, and the other elements contained in the dry mass (proportional passive). The theoretically superfluous ("used up") part of the dry mass, which is proportional to the fraction of the propellant consumed, continues to stay on board the rocket as ballast, and energy is wasted upon its acceleration. Failure to jettison the proportional passive thus has a harmful effect and prevents simple rockets from reaching escape velocities. To obviate this bad effect Tsander and Kondratyuk evolved the idea of transforming the no longer useful parts of the spaceship into supplementary fuel.

Tsiolkovskii also knew about the high calorific capacity of metallic fuels, but his investigations brought him to the conclusion that solid components could not be used as rocket fuel. Discussing the suitability of different rocket fuel components Tsiolkovskii wrote: "Carbon alone is unsuitable because of its solidity. Silicon, aluminum, calcium, and other substances will not do, not only because of their solidity, but because the products of their combination with oxygen are nonvolatile . . . The formation of steam liberates 32 to 33 cal/gram. The combustion of light metals — lithium, aluminum, magnesium, as well as silicon and boron — gives from 3400 to 5100 calories, i.e., considerably more, but these materials are not suitable because of their nonvolatile products."**

Unlike Tsander and Kondratyuk, Tsiolkovskii concentrated all his attention on ordinary multistage rockets, operating on "prosaic" fuels † (to use Tsiolkovskii's expression), with jettisoning of the no longer useful stages.

In our own days rocketry has followed the path chosen by Tsiolkovskii, but work remains to be done on the question of using solid propellants which might also temporarily serve as elements of the dry mass.

* Kondratyuk, Yu.V. "Zavoevanie mezhplanetnykh prostranstv" (The Conquest of Interplanetary Space), p.28, 1947.

** Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works) Vol.II, pp.371-372.

† Ibid., p.161.

Tsiolkovskii first expressed the idea of a composite rocket in 1918, in his story "Vne Zemli" (Beyond the Earth), partially published in the magazine "Priroda i lyudi" (it was published in full in 1920). He wrote: "It was only a step from the simple to the composite rocket, which was composed of many simple ones. Generally speaking, it was a body streamlined for minimum resistance, 100 meters long and 4 meters wide, something like a gigantic spindle. It was divided by transverse partitions into 20 sections, each of which was a jet craft containing a supply of explosive, a detonating chamber with independently functioning injector, detonating pipe, etc."*

In the story, which Tsiolkovskii began to write as early as 1896, a group of scientists, headed by the Russian Ivanov (the group also included an Italian, Galileo; an Englishman, Newton; a Frenchman, Laplace; a German, Helmholtz; and an American, Franklin), design and construct, in the year 2017, a space rocket, in which they fly around the earth, and afterwards send an expedition to the moon. According to the tale, "the rocket had a volume of 800 cubic meters and could displace 800 tons of water. Less than a third of this volume (240 tons, or 240 cubic meters) was occupied by two liquids that exploded in stages, discovered by our Franklin. The explosive energy of this mass was enough to accelerate the rocket fifty times to a velocity at which it could eternally travel away from the solar system and to decelerate it from that velocity fifty times. The rocket casing, fully equipped, weighed 40 tons, of which supplies, instruments, and greenhouses totalled 30 tons. The total weight of everything else, including the passengers, was under 10 tons. The rocket with all its contents thus weighed one third as much as the explosive."

From this description it can be deduced that this space rocket had a Tsiolkovskii coefficient $z = 3$, and consequently, in order to obtain the indicated 100 times escape velocity (16.7 km/sec), a propellant with a gas exhaust stream velocity $c \approx 1,200,000$ m/sec would be required. Evidently Franklin made an effort and invented a completely new form of energy comparable only to nuclear energy. The indicated parameters ($z = 3$, $c = 12 \cdot 10^5$) would permit the rocket described to reach the escape velocity of 16.7 km/sec fifty times, and to decelerate from it to a standstill as many times; or, for constant acceleration, to achieve a terminal velocity of roughly $5.5 \cdot 10^{-3}$ times the velocity of light.

Of course, the figures given and Tsiolkovskii's corresponding calculations were well known from the beginnings of his work on the theory of space flight, but Franklin . . . failed to put in an appearance, atomic energy was still firmly under lock and key, and the only remaining way out was to abandon the idea of a simple rocket and seek a solution of the problem in a more complex design for the rocket itself.

Tsiolkovksii's multistage rocket received its name and a contemporary structural form (at least insofar as the solution of its fundamental problems was involved) in his work "Issledovanie mirovykh prostranstv reaktivnymi priborami" (The Investigation of Space by Jet Machines), (1926). In this work Tsiolkovskii presented complete mathematical calculations for a two-stage rocket, reinforcing them with detailed numerical tables. Tsiolkovskii's two-stage rocket was two rockets consecutively joined—a "land" rocket (the first stage), which acted as a carrier for the second stage and returned to the earth after the

* Tsiolkovskii, K.E. "Vne Zemli" (Beyond the Earth). Izdatel'stvo AN SSSR, pp. 40-41. 1958.

fulfilment of its tasks, and a "sky" rocket (the second stage), which would reach escape velocity. "It is clear," Tsiolkovskii wrote, "that while still on the earth the rocket must acquire some velocity in order to begin ascending flight immediately, horizontally or on an incline. The higher the velocity acquired in the take-off run, the better. It is desirable that the missile not expend for this purpose the reserve energy that it carries in the form of explosives, and that can only be the case if the rocket is set in motion by an outside force: automobile, steamship, locomotive, airplane, dirigible, gas or electromagnetic cannon, etc. Existing means cannot give velocities of above 100 to 200 m/sec, because wheels and propellers cannot revolve faster than that without breaking. Their extreme maximum velocity can be brought to 200 m/sec — no more. Ordinary means of movement cannot exceed this velocity (720 km/hour). For a beginning, even this is much, but we would try to give the rocket as high a preliminary velocity as possible, so that it could save its reserve of explosive for subsequent flight, when it abandons its land journey. From this it is clear that special means are required to impart velocities above 200 m/sec. Gas or electromagnetic cannon must be rejected out of hand because of their enormous cost, which runs into millions, on account of their great length. In short cannon the force of the recoil would break everything. A rocket or jet method would be the simplest and cheapest in this case. I mean that our space rocket must be mounted on, or placed inside, another, land rocket."*

In this article Tsiolkovskii not only gave the theory of the motion of a two-stage rocket and a detailed description of the design of both stages, but also presented a concrete numerical calculation for a ten-ton subrocket. Supposing the dry mass of the land stage to be 10 tons, Tsiolkovskii worked out a table of values for the fuel supplies of the land stage q_2^T required to give the designated boost velocity ΔV_2 to the space stage. Here is a part of the table, for $c = 4000$ m/sec:

ΔV_2	2772	3660	4392
z_2	1	1.5	2
q_2^T	20	30	40

Here ΔV_2 is the increment in velocity of the first (space) stage, occasioned by the work of the engines of the second (land) stage; z_2 is Tsiolkovskii's number for the second stage, that is, the ratio of the mass of fuel of the second stage to the finite mass of the second subrocket.

He then found the values of z_1 required for a space rocket that had obtained some boost velocity ΔV_2 (Tsiolkovskii took $\Delta V_2 = 3$, 4, 5 km/sec) from the land stage to attain one of the three escape velocities. Here is a part of this table for $c = 5000$ m/sec and $\Delta V_2 = 4000$ m/sec:

V_*	8	11	17
z_1	1.24	3.08	12.0
z_*	4	8	30

Here z_* is Tsiolkovskii's coefficient for a single rocket equivalent to the two-stage rocket; $z_* = (1+z_1)(1+z_2)-1$.

This table clearly shows the chief advantage of the multistage rocket.

In the 1926 edition of "Issledovanie mirovykh prostranstv reaktivnymi priborami" Tsiolkovskii described the simplest version of the multistage rocket. Later, in his paper "Kosmicheskie raketnye poezda" (Cosmic Rocket

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol. II, p. 234.

Trains), he developed the idea of multistage rockets differently. In this work Tsiolkovskii gave a detailed description of the structure and working principle of the multistage rocket, together with its detailed theory and mathematical calculation of its most important flight characteristics; and he projected four possible versions, designating them A, D, B, and C,* which will henceforth be referred to as "Tsiolkovskii rockets." Tsiolkovskii himself studied the first three (A, D, B) in detail, and although he did not give the fourth (C) such thorough consideration, he regarded it as the most expedient from a practical point of view.**

One of the chapters of Tsiolkovskii's last, unfinished work is also devoted to the subject of multistage rockets. This chapter is published in volume II of Tsiolkovskii's Collected Works.

Although Tsiolkovskii was fully convinced of the superiority of the principle of multistage rockets, which he had mathematically established in the years 1926 to 1929, he evidently considered that its technical realization would come only in the relatively distant future. Foreseeing numerous difficulties in the realization of piloted rocket flight, he was a supporter of gradual advances in this great work.

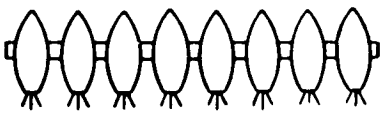

FIGURE 1

Tsiolkovskii recommended caution in attempting the mastery of more complicated, and consequently, more risky types of rockets, and suggested beginning with the simplest versions. His article "Naibol'shaya skorost' rakety" (The Maximum Velocity of a Rocket) was an exposition of exactly this point of view.

In this paper, dating from the last year of Tsiolkovskii's life, he suggested together with the ordinary multistage rocket a simplified version of it. Tsiolkovskii called the regular multistage rocket (of 1926 and 1929) a "rocket train." In it the process of propellant combustion took place in consecutive stages, beginning with the n-th stage (the biggest) and ending with the first, with any i-th stage being jettisoned immediately after the consumption of its propellant.

Tsiolkovskii referred to the simplified version of his multistage rocket (1935) as a "rocket squadron." The squadron consisted of 2^n comparatively small identical rockets, placed not consecutively, but parallel in a chain (Figure 1). All of the rockets in the squadron had identical fuel supplies and conventional low-powered rocket engines. Upon launching, the engines of all the rockets were started. After consumption of half the fuel supply half of the rockets in the squadron, i.e., 2^{n-1} rockets, poured their remaining fuel into the tanks of the other half, after which they were jettisoned and glided to earth.

The other half of the squadron, having received a full supply of fuel, continued in flight, gaining altitude and velocity. After consumption of half

* Ibid., p. 321.

** Ibid., p. 322, par. 89.

the fuel, half, i.e. 2^{n-2}, of the rockets left in the squadron poured their remaining fuel into the tanks of the other half, and were then jettisoned, etc. The last rocket, carrying the payload, attained the maximum velocity and altitude. In this way, it will be noted that a squadron of 2^n rockets could provide $n+1$ subsquadrons and n fuel transfers.

Tsiolkovskii gave a formula for the determination of the ideal velocity communicated by such a squadron to the payload:

$$V_* = c \ln \frac{(1+z)^{n+1}}{(1+0.5z)^n}.$$

On the basis of this formula Tsiolkovskii worked out a table* of velocities (for $c = 3000$ m/sec, $z = 4$), part of which is here given:

Number of rockets . . .	1	2	4	8	16
V_*	4827	6361	7895	9429	10962

If a rocket train were to be built from the 2^n rockets in the squadron, the result would evidently be a multistage rocket of type A or D (this follows from the fact that all the rockets of the squadron are identical). Comparing similar tables for the squadron and the train corresponding to it shows that for relatively large n (the tables constructed are for 16 rockets in the squadron or train, i.e., for $n = 4$), the squadron and corresponding train are almost equivalent with respect to the V_* they give. The train has a small advantage, but this negligible superiority can be realized only in "free space"; in a gravitational field the train (i.e., a multistage rocket of type A or C) would be totally unable to move on account of the small thrust of the engines of the consecutive stages. The squadron has no difficulty in leaving the surface of the earth, since the engines of all the rockets are operating simultaneously. Thus, to ignore big problems for the time being, and think instead of ordinary flights to high altitudes (up to 2000 or 3000 km), with the object of giving man proficiency in piloting cosmic rockets, Tsiolkovskii's "squadrons" seem to me to resolve the preliminary problem of training flights in the part of outer space closest to the earth better than more complicated multistage rockets. Tsiolkovskii himself took the same view of "squadrons," and wrote on the subject as follows:

"I earlier proposed for this purpose (i.e., for the attainment of escape velocities.— V. K.) artificial terrestrial roads and rocket trains. Such things are certainly correct and possible but not applicable at the present time because of their costliness and for other reasons... All of these trains and "cannon" will find use in the distant future, when the significance of interplanetary travel will have grown and will attract more of man's attention, will awaken more faith and real hopes... The method of a group of the first low-powered machines (i.e., squadrons — V. K.) and the transfer of propellant is more accessible to the state of mind of contemporary man. One rocket-propelled aircraft will prompt a subsequent experiment with two identical and imperfect craft."**

Here Tsiolkovskii also points out that the cheapness and simplicity of design of rocket-propelled aircraft would permit the organization of rocket sport, which would rapidly advance man's command of the controlled flight of rocket squadrons. "Experiments with several rocket-propelled craft,"

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol. II, p. 426.
** Ibid., p. 429.

wrote Tsiolkovskii, "will take place as interesting stunts, by the way. But these stunts will inevitably lead to the achievement of escape velocities."*

Tsiolkovskii thus gave, in this paper on rocket squadrons, a completely original solution to the problem of using the new step-rockets for training flights for the pilots of spaceships.

With multistage rockets mankind immediately marched confidently into the era of space conquest. Tsiolkovskii wrote, "Mankind's first great step will consist of flying beyond the atmosphere and creating an earth satellite. The rest, even leaving our solar system, will be relatively easy."** Tsiolkovskii had expressed the idea of building an artificial earth satellite as early as 1903 in "Issledovanie mirovykh prostranstv reaktivnymi priborami."†

"Mankind's first great step" was taken by Soviet science on 4 October, 1957, and was a triumphant vindication of Tsiolkovskii's ideas.

In 1935 Tsiolkovskii wrote, "The more I worked, the more I came upon various difficulties and obstacles. Until very recently I supposed that centuries would be needed to realize flights with escape velocities (8 to 17 km/sec), and this idea was confirmed by the weak results obtained here and abroad. But most recently ceaseless work has shaken these pessimistic views of mine; methods have been found (multistage rockets—V.T.), which will give amazing results in a matter of decades.

"The attention devoted by our Soviet government to the development of industry and of every sort of scientific research in the USSR will, I hope, confirm my expectations."††

These hopes of the father of cosmonautics, as we know, were confirmed by Soviet science only two decades later. In 1957 a Soviet multistage rocket attained circular velocity (8 km/sec). In 1959 escape velocity, above 11 km/sec, was attained. In 1961 the first space flight of a Soviet citizen occurred, in the ship "Vostok."

Soviet science has hoisted the flag of space navigation.

THE EQUATION OF MOTION OF A SIMPLE (SINGLE) ROCKET

The fundamental law of rocket motion (Tsiolkovskii's equation)

Following Tsiolkovskii's method,‡ the rocket, together with the fuel which constitutes the source of its propulsive energy, will be regarded as an isolated (in the mechanical sense) system. The theorem of momentum change leads to the conclusion that the momentum of a given system must be conserved in the face of any mechanical interactions taking place within the system.

* Ibid.
** Ibid., p. 208.
† Ibid., p. 94.
†† Ibid., p. 419.
‡ Ibid., pp. 76–77.

Let M and $\bar{V}$ designate the mass and velocity of the rocket at any moment of time t. At the moment $t_1 = t + \Delta t$ these quantities will be M_1 and $\bar{V}_1$:

$$M_1 = M + \Delta m; \quad \bar{V}_1 = \bar{V} + \Delta \bar{V}.$$

Let Δm denote the mass of fuel consumed and ejected by the engine of the rocket in the time Δt.

$$\Delta m = -\Delta M.$$

For the isolated system (rocket + fuel particle Δm), the law of conservation of momentum can be written

$$\bar{Q} = \bar{Q}_1$$

or

$$M\bar{V} = M_1\bar{V}_1 + \Delta m\bar{u}, \qquad (\alpha)$$

where $\bar{u}$ is the absolute ejection velocity of the particle Δm. Designating by $\bar{c}$ the ejection velocity of the particle Δm relative to the coordinate system advancing with velocity $\bar{V}$ gives

$$\bar{u} = \bar{c} + \bar{V}.$$

Substituting for $\bar{u}$, $\bar{V}_1$ and M_1 in (α) their values from the relationships adduced above gives

$$M\bar{V} = (M + \Delta M)\ (\bar{V} + \Delta \bar{V}) - \Delta M\ (\bar{c} + \bar{V}).$$

After simplification, taking the limit as $\Delta t \to 0$ gives

$$M\frac{d\bar{V}}{dt} = \frac{dM}{dt}\bar{c}. \qquad (\beta)$$

Equation (β) is essentially the same as Tsiolkovskii's equation (8)* and I. V. Meshcherskii's equation (10).**

Equation (β) is the differential equation of motion for a simple (single) rocket in "free space," i. e., in space without gravity or a resisting medium. I. V. Meshcherskii, the founder of the mechanics of variable masses, showed that equation (β) governs not only the motion of a rocket, but the motion of any point of variable mass. Equation (β) is therefore called Meshcherskii's equation for the motion of a point of variable mass. Tsiolkovskii derived this equation specially for the case of a rocket, independently of Meshcherskii.

Reactive force

In order to put equation (β) in ordinary dynamic form, i. e., in the form of Newton's Second Law (the product of the mass of the moving point and its acceleration is equal to the motive force applied to it), it must be shown that the right-hand side of the equation is an ordinary force in the sense of Newtonian mechanics. I do not regard discussion on this subject† as

* Ibid., p. 77.

** Meshcherskii, I.V. "Raboty po mekhanike tel peremennoi massy" (Papers on the Mechanics of Bodies of Variable Mass) (Klassiki estestvoznaniya), p. 68. Moskva-Leningrad, 1949.

† "Reaktivnoe dvizhenie," No. 2. Scientific and Technical Information Department (ONTI), Moskva, 1936.

having settled the question. A logically rigorous proof of this proposition can be obtained only through a kinetic method of determining the force.

The following general definition of the concepts of mechanical force, which is also applied to other types of mechanical interactions, will be taken as a starting point.*

The momentum lost by the particle A_1 (i.e., the decrease in its momentum) per unit of time is called the force developed in the time Δt by the particle A_1 of mass m_1 in its interaction with the particle A_2 of mass m_2,

$$(\overline{F}_2)_1^* = \frac{-\Delta_2(m_1\overline{V}_1)}{\Delta t}. \qquad (\gamma)$$

Equation (γ) defines the mean force developed in the time Δt by A_1 in the process of its interaction with A_2.

The limit of the mean value of the force as $\Delta t \to 0$ is called the true, or instantaneous value of the force

$$(\overline{F}_2)_1 = \lim_{\Delta t \to 0} (\overline{F}_2)_1^* = -\frac{d_2(m_1\overline{V}_1)}{dt}.$$

The force $(\overline{F}_2)_1$, with which particle A_1 acts on particle A_2, is a vector applied to particle A_2. The external subscript "1" on the force denotes its material source (in this case the particle A_1), and the internal subscript "2" denotes the object to which this force is applied (i.e., the particle A_2). It is easy to show** that the force defined in this way satisfies all of Newton's fundamental laws.

Using this definition of the force, the mean value of the force developed by the ejected fuel particle Δm can be found. The result, in accord with (γ), is

$$(\overline{F}_2)_1^* = \frac{-\Delta\bar{q}}{\Delta t},$$

where $\Delta\bar{q}$ is the increment in the momentum of the ejected particle Δm in time Δt, and consequently, $(-\Delta\bar{q})$ is the momentum it loses:

$$\Delta\bar{q} = \Delta m\bar{u} - \Delta m\overline{V} = \Delta m(\bar{c} + \overline{V} - \overline{V}) = -\Delta M\bar{c}.$$

Then

$$(\overline{F}_2)_1^* = \frac{\Delta M}{\Delta t}\bar{c}$$

or, taking the limit as $\Delta t \to 0$,

$$(\overline{F}_2)_1 = \frac{dM}{dt}\bar{c}.$$

Here the external subscript denotes the source of the force (in this case, the ejected mass Δm), and the internal subscript, the object to which the force is applied (in this case, the rocket). It has therefore been demonstrated that the gas exhaust stream actually does develop a force which is applied to the rocket and which is represented by the right-hand side of equation (β). This force is called reactive, and will from now on be designated $\bar{R}$.

The right-hand side of Tsiolkovskii's equation (8) is thus the pulse $\bar{R}dt$ of the reactive force.†

* Papers of the Institute of the History of Natural Science and Engineering, Academy of Sciences of the USSR, Vol.5, pp.66-67. 1955.

** Ibid., pp.67-68.

† Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II. p.77.

The law of reactive force established by Tsiolkovskii* can thus finally be written:

$$R = \frac{dM}{dt}\bar{c}. \tag{I}$$

If external forces (gravity, resistance of the medium, etc.) are also acting on the rocket, and their resultant is designated by $\bar{F}$, the equation of Tsiolkovskii and Meshcherskii is rewritten in the more general form

$$M\frac{d\bar{V}}{dt} = \bar{R} + \bar{F}. \tag{II}$$

Equation (II) and the law of reactive force (I) will be applied to the solution of the simplest problems of rocket motion, which are considered in detail in Tsiolkovskii's papers.

Tsiolkovskii's formula for ideal rocket velocity

The motion of a simple rocket in "free space" will be considered, accepting Tsiolkovskii's hypothesis that the gas exhaust stream has a velocity $\bar{c}$ constant in magnitude and directed opposite to the velocity $\bar{V}$ of the rocket. Taking the projections of both sides of equation II (for $\bar{F} = 0$) on to the direction of motion of the rocket gives

$$M\frac{dV}{dt} = -\frac{dM}{dt}c$$

or

$$\frac{dM}{M} = -\frac{dV}{c}.$$

The general solution of this differential equation is written in the form

$$\ln M = -\frac{V}{c} + c'.$$

Putting $t = 0$, $V = V_0$, and $M = M_0$ gives

$$c' = \ln M_0 + \frac{V_0}{c},$$

and the particular solution is then

$$V^i = V_0 + c\ln\frac{M_0}{M}, \tag{1}$$

where V^i denotes the "ideal" velocity of the rocket, i.e., the velocity in "free space." The terminal velocity $V^i_к$, attained after depletion of the entire fuel supply (and assuming $V_0 = 0$), is obtained from equation (1):

$$V^i_к = c\ln\left(1 + \frac{M_т}{M_к}\right).$$

Tsiolkovskii obtained this formula independently of Meshcherskii in 1896–1898, and he first published it in 1903.** The ratio of the propellant mass $M_т$ to the terminal mass of the rocket $M_к$, i.e., the relative fuel supply, is

* Meshcherskii called the reactive force "additional force." See Meshcherskii, I.V., "Raboty po mekhanike tel peremennoi massy" (Papers on the Mechanics of Bodies of Variable Mass) (Klassiki estestvoznaniya), p.67.

** Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.77.

one of the fundamental characteristics of rockets and is called Tsiolkovskii's coefficient (or number). Tsiolkovskii's number is designated by z, $\frac{M_т}{M_к} = z$.

The velocity $V_к^i$, attainable under ideal conditions (in "free space") is called the ideal velocity of the rocket; it is the upper limit of the actually attainable velocities for a given Tsiolkovskii number z and a given combustion product exhaust velocity $\bar{c}$. Tsiolkovskii's equation for ideal velocity can be written down in the final form

$$V_к^i = c \ln(1 + z). \tag{2}$$

Tsiolkovskii formulated this fundamental law of ideal rocket velocity in the words: "When the mass of the rocket plus the mass of the propellant contained in the jet engine increases in geometric progression, the velocity of the rocket increases in arithmetic progression."* Such a formulation of Tsiolkovskii's law describes a variant of equation (2):

$$V_к^i = c \ln \frac{M_0}{M_к}.$$

If, in fact, the initial mass takes on a series of values in increasing geometrical progression:

$$M_0,\ 2M_0,\ 4M_0,\ldots,$$

$V_к^i$ takes on a series of values in increasing arithmetic progression:

$$V_к^i,\ V_к^i + c\ln 2,\ V_к^i + 2c\ln 2,\ V_к^i + 3c\ln 2,\ldots$$

From equation (2) Tsiolkovskii drew an important conclusion: the ideal velocity of the rocket is independent of the engine rating.

Two laws of fuel consumption by a rocket engine

Although the ideal velocity of the rocket does not depend on the engine rating (that is, on the rapidity of fuel consumption), the acceleration and reactive force are, of course, dependent on the rate of fuel consumption, as is clear from the very form of laws (I) and (II).

Let us find a law of mass consumption which will give the rocket a constant acceleration

$$w^i = \text{const},$$

where w^i is the "ideal" acceleration of the rocket, i.e., in "free space."

Equation (II) gives

$$\frac{dM}{M} = -\frac{w^i}{c} dt.$$

Integrating this equation and using initial conditions ($t = 0$, $M = M_0$) then gives

$$M = M_0 e^{-\alpha t}, \tag{3}$$

where α is the coefficient of mass consumption:

$$\alpha = \frac{w^i}{c}.$$

* Ibid., p. 142.

The law of mass consumption (3) shows that α characterizes the rate of decrease of $\ln M$ or the rate of fuel consumption per unit of mass:

$$-\alpha = \frac{d}{dt} \ln M = \frac{1}{M}\left(\frac{dM}{dt}\right).$$

It is therefore clear that for fuel consumption according to law (3) (the so-called exponential law of mass consumption) the rocket will move with the constant acceleration

$$w^{1} = \alpha c. \tag{4}$$

The inverse proportionality between the coefficient of consumption α and time required for burnout τ easily follows from (3):

$$\tau = \frac{1}{\alpha} \ln (1 + z). \tag{5}$$

In the case of instantaneous burnout, therefore, $\alpha = \infty$, and for infinitely slow combustion $\alpha = 0$.

Let us now find a law of mass consumption for a rocket flight with constant reactive force:

$$R = \text{const.}$$

Tsiolkovskii's law (I) gives

$$dM = \frac{R}{c}\, dt.$$

Integrating this equation for the initial conditions $t = 0$ and $M = M_0$ and designating the constant quantity R/cM_0 by α (the coefficient of mass consumption) gives

$$M = M_0(1 - \alpha t). \tag{6}$$

which is called the linear law of mass consumption. Consequently, fuel combustion according to (6) will assure a rocket flight with constant jet thrust

$$R = c\alpha M_0. \tag{7}$$

The coefficient of mass consumption in the linear law (6) also characterizes the relative velocity of combustion of the fuel

$$\alpha = -\frac{1}{M_0}\left(\frac{dM}{dt}\right).$$

Supposing that where the exponential law of mass consumption applies, at can take on any positive values, for the case of the linear law, $at \leqslant 1$. If the contrary were true the mass of the rocket M would take on a negative value.

Finally, let us find the relationship between the burnout time τ and the coefficient of mass consumption. The combustion law (6) gives at the moment of engine shutoff

$$M_к = M_0(1 - \alpha\tau),$$

from which it follows that

$$\alpha\tau = \left(1 - \frac{M_к}{M_0}\right)$$

or

$$\tau = \frac{1}{\alpha}\left(\frac{z}{1+z}\right). \tag{8}$$

The motion of a simple rocket in "free space" (Tsiolkovskii's first problem)

This problem may be stated as the study of rocket motion in "free space," i.e., in space free from gravity and a resisting medium. The current and terminal velocities of a rocket moving in "free space" are determined, for any law of mass consumption, by formulas (1) and (2). The law of distance change is obtained by integration of the equation

$$dS = V_0 dt + c \ln \frac{M_0}{M} dt.$$

Applying the linear law of combustion,

$$M = M_0(1 - \alpha t)$$

gives the above equation the form

$$dS = V_0 dt - c \ln(1 - \alpha t)\, dt.$$

whose solution, found from a table of integrals, is

$$S = V_0 t + \frac{c}{\alpha}\{(1 - \alpha t)\ln(1 - \alpha t) + \alpha t\} + c'.$$

For initial conditions $t = 0$, $S_0 = 0$, the constant $c' = 0$, and the final solution is

$$S^{\text{i}} = V_0 t + \frac{c}{\alpha}\{(1 - \alpha t)\ln(1 - \alpha t) + \alpha t\}, \qquad (9)$$

where S^{i} is the rocket's "ideal" path, i.e., its path in "free space."

For the exponential law of mass consumption $M = M_0 e^{-\alpha t}$ the rocket will move with the constant acceleration $w^{\text{i}} = \alpha c$, and the law of uniformly accelerated motion therefore gives (for $S_0 = 0$)

$$S^{\text{i}} = V_0 t + \frac{1}{2}\alpha c t^2. \qquad (10)$$

For distances at the end of the rocket's motorized flight, that is, for the termination of the boost phase trajectory, the result is

$$S^{\text{i}}_{\text{к}} = V_0 \tau + \frac{c}{\alpha}\{(1 - \alpha\tau)\ln(1 - \alpha\tau) + \alpha\tau\} \qquad (9')$$

for the linear law of combustion and

$$S^{\text{i}}_{\text{к}} = V_0 \tau + \frac{1}{2}\alpha c \tau^2 \qquad (10')$$

for the exponential law of combustion.

It is evident that the ideal ranges of the rocket, unlike its ideal velocities, are dependent on the engine rating (on the time τ required for combustion of the propellant).

The motion of a simple rocket in a uniform gravity field (Tsiolkovskii's second problem)

Tsiolkovskii thoroughly studied all aspects of the motion of a rocket in uniform and variable gravity fields. Gravity considerably increases the

relative fuel supply, characterized by Tsiolkovskii's number z, required for the attainment of escape velocities; it imposes definite limits on the different parameters related to the realization of optimum flight conditions, lowers the rocket's efficiency, etc. Here only very simple questions of the dynamics and kinematics of a rocket moving in a uniform gravity field, which arise in considering the motion of multistage rockets, will be taken up.

Tsiolkovskii's second problem, then, is to study the vertical motion of a rocket in a uniform gravity field characterized by the constancy of its acceleration vector:

$$g = \text{const.}$$

Where the exponential law of combustion applies the problem is quickly solved, because the acceleration w of the rocket remains constant:

$$w = w^{\text{i}} - g = ac - g. \tag{11}$$

Application of the law of uniformly accelerated motion then gives

$$V = V_0 + (ac - g)t; \tag{12}$$

$$S = V_0 t + \frac{1}{2}(ac - g)t^2. \tag{13}$$

The unsubscripted kinematic quantities w, V, and S refer to rocket flight in a gravity field. Let them be expressed in terms of the corresponding quantities for rocket flight in "free space":

$$V = V^{\text{i}} - gt; \tag{12'}$$

$$S = S^{\text{i}} - \frac{dt^2}{2}. \tag{13'}$$

Finally, the same quantities at the termination of the boost phase trajectory are written as follows:

$$V_{\text{к}} = V^{\text{i}}_{\text{к}} - g\tau; \tag{12"}$$

$$S_{\text{к}} = S^{\text{i}}_{\text{к}} - \frac{1}{2}g\tau^2, \tag{13"}$$

where $S^{\text{i}}_{\text{к}}$ is determined by formula (10'). The time of boost phase flight τ is determined, as in "free space," by formula (5).

Formulas (12') and (13'), as well as (12") and (13"), are equally valid for cases where the linear law applies, except that the time τ is then determined by formula (8). Substituting in (12) and (13) the expressions for ideal velocity and range given in formulas (1) and (9) gives:

$$V = V_0 - c\ln(1 - \alpha t) - gt, \tag{14}$$

$$S = V_0 t + \frac{c}{\alpha}\{(1 - \alpha t)\ln(1 - \alpha t) + \alpha t\} - \frac{gt^2}{2} \tag{15}$$

and correspondingly:

$$V_{\text{к}} = V^{\text{i}}_{\text{к}} - g\tau; \tag{14'}$$

$$S_{\text{к}} = S^{\text{i}}_{\text{к}} - \frac{1}{2}g\tau^2, \tag{15'}$$

where $S^{\text{i}}_{\text{к}}$ is determined by formula (9').

For rocket flight in a gravity field, therefore, unlike rocket flight in "free space," the terminal velocity of the rocket (velocity at the end of the boost phase) depends on the fuel combustion time τ, and, as is evident from

(12') and (14'), is a maximum for instantaneous fuel combustion, i.e., for $\tau = 0$ or $\alpha = \infty$.

It is easy to show that in a gravity field a rocket with a given fuel supply will reach maximum altitude for instantaneous fuel combustion, or, what amounts to the same thing, that if combustion is instantaneous a rocket will reach a specified velocity with minimum fuel consumption.

TSIOLKOVSKII'S MULTISTAGE ROCKETS (GENERALIZED TYPE)

Fundamental concepts and terminology

Simple or single is the name given to the rocket whose structural elements are preserved unchanged during its flight. If, however, the rocket is composed of several assemblies or stages (as in the designs of Kondratyuk and Tsiolkovskii) which are successively jettisoned in the course of flight, it is termed multistage, or, by some writers, staged. Here the term "staged rocket" will be given a more limited sense, and taken to mean a rocket whose structural elements do undergo change during flight, but whose parts, having exhausted their usefulness, are sent to the combustion chamber to be used as fuel, rather than jettisoned (designs of Tsander and Kondratyuk).

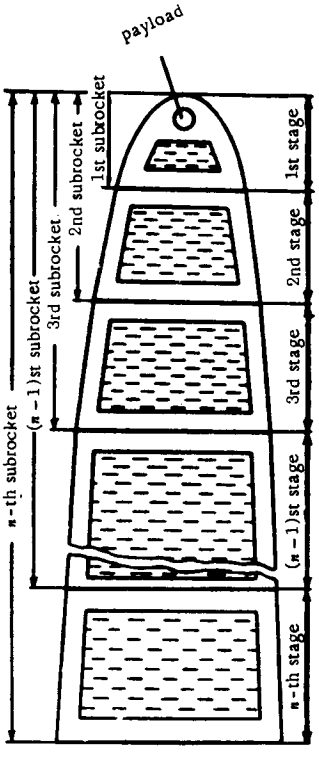

FIGURE 2

A multistage rocket of n stages consists then of n simple rockets, which are successively jettisoned during flight, after their fuel is completely consumed. These simple rockets are termed the stages of the multistage rocket. At the initial moment of time (launching), the engines of the most powerful stage are started.

After consumption of the fuel supply of the first stage, it is jettisoned together with its engines and other equipment, and returns to the earth, and immediately or shortly thereafter the engines of the second stage are started. The altitude and velocity of the payload, which is located in the n-th and last stage, or head rocket, thus continue to increase, and the process of jettisoning stages can continue up to the n-th stage. Whether the last stage is also to be jettisoned or continues to carry the payload depends on the purpose of the rocket. In what follows it will be assumed that the engines of a given stage are started at the moment that the preceding one is jettisoned.

Each stage of a multistage rocket has its own propellant and engines. In what follows, stages will be counted beginning, not with the launching stage, but with the head containing the payload (an artificial earth satellite or a satellite-ship with pilot's cabin, etc.), so that the engines of the n-th stage will be those

started at launching, followed by those of the $(n-1)$st, $(n-2)$nd, etc., up to the first stage, or head.

The collection of the first i stages (beginning from the head), propelled at the moment considered by the engines of the i-th stage, is called the i-th subrocket of the n-stage rocket (Figure 2).

The n-stage rocket contains n subrockets, of which the n-th is the multistage rocket itself at launching, and the first is the head rocket. The payload is considered a constituent of the subrocket, but not the stage.

In the course of flight the number of the operating stage and the subrocket corresponding to it decreases from n to unity ($i = n...1$).

The masses constituting the i-th stage will be designated by lower-case letters, while those constituting the i-th subrocket will be designated by capital letters:

$m_i^т$ — propellant mass of the i-th stage;
$M_i^т$ — propellant mass of the i-th subrocket;
$M_i^п$ — payload mass of i-th subrocket;
$m_i^к$ — dry mass of i-th stage;
$M_i^к$ — dry mass of i-th subrocket;
m_i^0 — initial mass of i-th stage;
M_i^0 — initial mass of i-th subrocket;
$m_i^к$ — terminal mass of i-th stage;
$M_i^к$ — terminal mass of i-th subrocket.

The scheme of the multistage rocket is illustrated in Figure 2.

A number of relationships between the masses of stages and subrockets can be written down:

$$m_1^0 = m_1^к + m_1^т,$$
$$M_1^0 = m_1^к + m_1^т + M_1^п.$$

The payload $M_1^п$ of the first subrocket (the head rocket) is actually the payload of the entire multistage rocket (satellite, cabin with cosmonauts, warhead, etc.).

Let the mass of the actual payload be designated by the Gothic letter $\mathfrak{m}$. Then

$$M_1^п = \mathfrak{m}.$$

For any i-th subscript,

$$m_i^0 = m_i^к + m_i^т;$$

$$M_i^0 = M_i^к + M_i^т - \mathfrak{m},$$

where

$$M_i^к = \sum_{\nu=1}^{i} m_\nu^к;$$
$$M_i^т = \sum_{\nu=1}^{i} m_\nu^т,$$

or

$$M_i^0 = m_i^к + m_i^т + M_i^п = m_i^0 + M_i^п = m_i^0 + M_{i-1}^0.$$

Evidently the payload mass $M_i^п$, carried by the i-th stage, is the initial mass of the $(i-1)$st subrocket M_{i-1}^0. The final masses of the i-th stage and subrocket are then:

$$m_i^к = m_i^0 - m_i^т = m_i^к; \quad M_i^к = M_i^0 - m_i^т = M_{i-1}^0 + m_i^к.$$

As remarked above, the payload mass is considered to constitute part of the mass of the subrocket, but not the stage. Let the flight time of the i-th

subrocket and the velocities attained and distances covered by it in this time be designated respectively τ_i, V_i, and S_i. The full time in which the engine of the i-th stage is operating during this period, and the increases in velocity and distance traveled will be designated respectively

$$\Delta\tau_i,\ \Delta V_i,\ \Delta S_i.$$

These quantities are related as follows:

$$V_i = \sum_{\nu=i}^{n} \Delta V_\nu; \quad S_i = \sum_{\nu=i}^{n} \Delta S_\nu; \quad \tau_i = \sum_{\nu=i}^{n} \Delta\tau_\nu; \tag{16}$$

$$V_i = V_{i+1} + \Delta V_i; \quad S_i = S_{i+1} + \Delta S_i; \quad \tau_i = \tau_{i+1} + \Delta\tau_i. \tag{17}$$

In particular, the full time of flight (from the moment of launching), terminal velocity, and distance covered during motorized flight by the head rocket or payload, are:

$$\begin{aligned} V_к &= V_1 = \sum_{\nu=1}^{n} \Delta V_\nu; \\ S_к &= S_1 = \sum_{\nu=1}^{n} \Delta S_\nu; \\ \tau_к &= \tau_1 = \sum_{\nu=1}^{n} \Delta\tau_\nu. \end{aligned} \tag{18}$$

Characteristic coefficients of a multistage rocket

The analysis of multistage rockets is carried out with reference to several coefficients that fully characterize the rocket type, and are therefore termed characteristic. They are determined as follows.

The Tsiolkovskii coefficient z_i of the i-th subrocket describes the relative fuel supply of the i-th subrocket ($m_i^т$), and is equal to the ratio of the propellant mass of the i-th stage to the terminal mass of the i-th subrocket:

$$z_i = \frac{m_i^т}{M_i^к}. \tag{19}$$

The "structural" coefficient s_i is the ratio of the initial mass of the i-th stage to its dry mass:

$$s_i = \frac{\bar{m}_i^0}{m_i^c}. \tag{20}$$

The "relative weight" of the i-th subrocket, or payload coefficient p_i, describes the mass of subrocket required for each unit mass of its payload:

$$p_i = \frac{M_i^0}{M_i^p} = \frac{M_i^0}{M_{i-1}^0}. \tag{21}$$

The three coefficients z_i, s_i, and p_i are interrelated, so that if two of them are regarded as independent, they may be used to determine the third. In fact, the defining formulas (19), (20), and (21) give

$$p_i = \frac{M_i^0}{M_{i-1}^0} = \frac{M_i^k + m_i^т}{M_i^k - m_i^c}.$$

Dividing both numerator and denominator by m_i^T gives

$$p_i = \frac{\frac{1}{z_i} + 1}{\frac{1}{z_i} - \frac{m_i^c}{m_i^T}}.$$

Transforming the second member of the denominator as follows,

$$\frac{m_i^c}{m_i^T} = \frac{m_i^c}{m_i^0 - m_i^c} = \frac{1}{s_i - 1}.$$

and substituting the result in the above equation gives, after further simplification,

$$p_i = \frac{(z_i + 1)(s_i - 1)}{s_i - z_i - 1}. \tag{22}$$

The most important performance characteristic of a multistage rocket is its "full relative weight," or full payload coefficient P, which equals the ratio of the multistage rocket's launching weight to the weight of its payload,

$$P = \frac{M_n^0}{\mathfrak{m}}. \tag{23}$$

from which it follows that

$$P = \frac{M_n^0}{M_{n-1}^0} \frac{M_{n-1}^0}{M_{n-2}^0} \frac{M_{n-2}^0}{M_{n-3}^0} \cdots \frac{M_3^0}{M_2^0} \frac{M_2^0}{M_1^0} \frac{M_1^0}{\mathfrak{m}}$$

or, on the basis of (21),

$$P = p_n p_{n-2} p_{n-2} \cdots p_3 p_2 p_1. \tag{24}$$

The coefficient P indicates how many kilograms of launching weight the multistage rocket in question must have for each kilogram of its payload $\mathfrak{m}$. The smaller this coefficient, the higher is the performance of the rocket.

Since the independent coefficients z_i and s_i determine p_i (22), they also determine P:

$$P = \prod_{\nu=1}^{n} \frac{(z_\nu + 1)(s_\nu - 1)}{s_\nu - z_\nu - 1}. \tag{25}$$

The representation of masses by characteristic coefficients

By equation (21),

$$M_i^0 = p_i M_{i-1}^0 = p_i p_{i-1} M_{i-2}^0 = \cdots = p_1 p_2 \ldots p_i \mathfrak{m}$$

or, on the basis of (22),

$$\widetilde{M}_i^0 = \prod_{\nu=1}^{i} \frac{(z_\nu + 1)(s_\nu - 1)}{s_\nu - z_\nu - 1} = P, \tag{26}$$

where $\widetilde{M}_i^0 = M_i^0 : \mathfrak{m}$, i. e., the initial mass of the i-th subrocket per unit of payload mass. Other masses marked above by a wavy line (tilde) have a similar meaning:

$$\widetilde{m}_i^T = m_i^T : \mathfrak{m}; \quad \widetilde{m}_i^c = m_i^c : \mathfrak{m}.$$

From (19),

$$\widetilde{m}_i^{\tau} = z_i \widetilde{M}_i^{\kappa} = z_i (\widetilde{M}_i^0 - \widetilde{m}_i^{\tau}),$$

which gives

$$\widetilde{m}_i^{\tau} = \frac{z_i}{1 + z_i} \widetilde{M}_i^0.$$

From (20)

$$\widetilde{m}_i^{c} = \frac{\widetilde{m}_i^0}{s_i} = \frac{\widetilde{m}_i^{\tau} + \widetilde{m}_i^{c}}{s_i},$$

which gives

$$\widetilde{m}_i^{c} = \frac{\widetilde{m}_i^{\tau}}{s_i - 1}.$$

Inserting in this equation the value of m_i^{τ} from (27) gives

$$\widetilde{m}_i^{c} = \frac{z_i}{(z_i + 1)(s_i - 1)} \widetilde{M}_i^0. \tag{28}$$

Finally,

$$\widetilde{M}_i^{\kappa} = \widetilde{M}_i^0 - m_i^{\tau}$$

or, on the basis of (27),

$$\widetilde{M}_i^{\kappa} = \frac{1}{z_i + 1} \widetilde{M}_i^0. \tag{29}$$

Equations (26), (27), (28), and (29) completely solve the problem of calculating the masses of a multistage rocket, its stages, and subrockets from given values of the independent characteristic coefficients z_i and s_i.

The law of increase of stage masses in a multistage rocket

Given the mass components of the head rocket (first subrocket), i.e., m_1^c, m_1^{τ}, $\mathfrak{m}$ (these quantities will be called the working parameters of the multistage rocket), the mass components of the following stages and subrockets will consecutively increase with their subscripts.

This dependence will be represented in the form:

$$\begin{aligned} m_i^{\tau} &= \psi_{\tau}(i)\, m_1^{\tau}; \\ m_i^{c} &= \psi_{c}(i)\, m_1^{c}, \end{aligned} \tag{30}$$

where $\psi(i)$ is an arbitrary function of the subscript i, taking on real finite values for $i = 1, 2 \ldots n$, and satisfying the condition $\psi_{\tau}(1) = \psi_c(1) = 1$.

The functions $\psi(i)$ will be called typifying functions, since their form fully defines the typical features of multistage rockets. This assertion follows from the fact that the independent characteristic coefficients are fully determined by the form of $\psi(i)$ and the working parameters, i.e., the masses of the first subrocket m_1^c, m_1^{τ}, and $\mathfrak{m}$.

First it will be shown how the masses of stages and subrockets can be expressed in terms of the typifying functions.

Representation of masses by typifying functions

Taking as given the typifying functions ($\psi_т$ and $\psi_с$) and the working parameters ($m_1^т$, $m_1^с$, $\mathfrak{m}$), we find

$$\widetilde{m}_i^т = \widetilde{m}_1^т \psi_т(i); \qquad \widetilde{m}_i^с = \widetilde{m}_1^с \psi_с(i); \tag{31}$$

$$M_i^* = M_i^т + M_i^с + \mathfrak{m} = \sum_{\nu=1}^{i} m_\nu^т + \sum_{\nu=1}^{i} m_\nu^с + \mathfrak{m}. \tag{32}$$

Turning to dimensionless (or relative) masses,

$$\widetilde{M}_i^0 = \sum_{\nu=1}^{i} \widetilde{m}_\nu^т + \sum_{\nu=1}^{i} \widetilde{m}_\nu^с + 1$$

or, on the basis of (31) and (32),

$$\widetilde{M}_i^0 = 1 + \widetilde{m}_1^т \sum_{\nu=1}^{i} \psi_т(\nu) + \widetilde{m}_1^с \sum_{\nu=1}^{i} \psi_с(\nu); \tag{33}$$

$$\widetilde{M}_i^к = 1 + \widetilde{m}_1^т \sum_{\nu=1}^{i-1} \psi_т(\nu) + \widetilde{m}_1^с \sum_{\nu=1}^{i} \psi_с(\nu); \tag{34}$$

$$\widetilde{M}_i^т = \widetilde{m}_1^т \sum_{\nu=1}^{i} \psi_т(\nu); \quad \widetilde{M}_i^с = \widetilde{m}_1^с \sum_{\nu=1}^{i} \psi_с(\nu). \tag{35}$$

Equations (31), (32), (33), (34), and (35) give a complete solution of the problem.

Representation of the independent characteristic coefficients by typifying functions

By (19),

$$z_i = \frac{\widetilde{m}_i^т}{\widetilde{M}_i^к}$$

or, on the basis of (31) and (34),

$$z_i = \frac{\widetilde{m}_1^т \psi_т(i)}{1 + \widetilde{m}_1^т \sum_{\nu=1}^{i-1} \psi_т(\nu) + \widetilde{m}_1^с \sum_{\nu=1}^{i} \psi_с(\nu)}. \tag{36}$$

Using (30), (31), and (32):

$$s_i = \frac{\widetilde{m}_i^т + \widetilde{m}_i^с}{\widetilde{m}_i^с} = 1 + \frac{\widetilde{m}_i^т}{\widetilde{m}_i^с};$$

$$s_i = 1 + \frac{\widetilde{m}_1^т \psi_т(i)}{\widetilde{m}_1^с \psi_с(i)}. \tag{37}$$

Since the remaining characteristic coefficients p_i and P are expressed in terms of the independent coefficients (in accordance with equations (22) and (25)), it follows that they are also determined by the typifying functions ψ.

Multistage Tsiolkovskii rockets of generalized type Ts

Multistage Tsiolkovskii rockets are those represented by equations (31) and (32). This definition is confirmed by the fact that type Ts rockets are the result of generalizing types A, B, C, and D, the last of which is a special form of the Ts rocket. It will be shown below that rockets A and D are completely described by the same typifying ψ functions:

$$\psi_\tau(i) = 1,\ \psi_c(i) = 1.$$

Rockets B and C are also described by the same typifying functions:

$$\psi_c(i) = \mu^{i-1};\quad \psi_\tau(i) = r^{i-1} + a\frac{r^{i-1} - \mu^{i-1}}{r - \mu},$$

where μ is a constant chosen out of the structural considerations:

$$r = 1 + \frac{\tilde{m}_1^\tau}{\tilde{m}_1^c + 1};\ a = \mu\tilde{m}_1^c : 1 + \tilde{m}_1^c.$$

Following Tsiolkovskii, both exponential ($M = M^0 e^{-\alpha t}$) and linear ($M = M^0(1 - at)$)* fuel combustion will be considered. The Tsiolkovskii rockets operating according to the exponential law of combustion, i.e., with constant acceleration, will be designated by the superscript α, e.g., Ts^α, and those operating according to the linear law, i.e., with constant jet thrust, will be designated by a subscript α, e.g., Ts_α.

Motion of the Ts^α rocket in free space

The regions of outer space sufficiently far from attracting masses so that the strength of gravity fields can be considered negligibly small and other possible dynamic effects, such as those of cosmic and solar radiation, cosmic particles and dust, etc., can be neglected, have approximately the same properties as "free space." In "free space," therefore, the only source of rocket acceleration is the rocket itself, whose engines eject the combustion products of the propellant contained in its tanks. It is assumed that the ejected particles of propellant do not interact with the mass of the rocket.

Assume that the engines of a rocket in free space are operating in accordance with the exponential law of combustion. For the i-th subrocket, at any moment of time during flight,

$$M_i = M_i^0 e^{-\alpha_i t},$$

where M_i is the current mass, i.e., the mass of the subrocket at a moment of time t; α_i is the coefficient of fuel consumption, supposed constant for the t-th stage.

In agreement with (4) for the exponential law of combustion,

$$w^n = c_i\alpha_i, \tag{38}$$

where c_i is the constant gas exhaust stream velocity of the i-th stage,

* [These expressions appeared previously (pp. 96 - 97) with M_0 instead of M^0. The author evidently adopts the superscript here because now the M^0 must also be subscripted (see, for example, the first formula below.]

driving the i-th subrocket. It will therefore be supposed here that all stages have identical acceleration w_i. Consequently, the a_i must be chosen corresponding to the c_i, in such a way that their product be a constant. Each i-th driving stage then communicates a constant accleration w_i^n to the subrocket it is driving. Operation of the engines of the i-th stage for a period of time $\Delta\tau_i$ results in an increase ΔV_i in the velocity of the i-th subrocket. On the basis of Tsiolkovskii's formula (1), assume

$$\Delta V_i^n = c_i \ln (1 + z_i). \tag{39}$$

The initial and terminal velocities of the i-th subrocket are then:

$$V_{i0}^n = V_{i+1}^n = \sum_{\nu=i+1}^{n} \Delta V_\nu^n;$$

$$V_i^n = V_{i+1}^n + \Delta V_i^n = \sum_{\nu=i}^{n} \Delta V_\nu^n.$$

From this the terminal velocity of the motorized flight of the head subrocket (or payload) can be found:

$$V_к^n = V_1^n = \sum_{i=1}^{n} \Delta V_i^n.$$

Substituting in this expression the value of ΔV_i^n from (39) gives:

$$V_к^n = c_\nu \ln \prod_{\nu=1}^{n} (1 + z_\nu). \tag{40}$$

In particular, for identical exhaust velocities $(c_\nu = c)$,

$$V_к^n = c \ln \prod_{\nu=1}^{n} (1 + z_\nu). \tag{41}$$

Formulas (40) and (41) clearly show the superiority of multistage to simple rockets. Since the values of c and z are limited for ordinary chemical propellants (in practice $z < 11$ and $c < 4000$ m/sec), so is the terminal velocity of a simple rocket,

$$V_к^n = c \ln (1 + z). \tag{42}$$

For $c = 4000$ m/sec and $z = 11$, $V_к^n = 9950$ m/sec. It follows that even in "free space" a simple rocket cannot attain escape velocity (about 11,200 m/sec). On the other hand, multistage rockets running on the same type of propellant ($c = 4000$ m/sec) can reach any escape velocity, as will now be shown.

Let an imagined simple rocket be made to conform fully with a given multistage rocket, having the same kind of propellant (i.e., having the same exhaust velocity c) and the same terminal velocity $V_к^n$. These rockets will be termed equivalent. Use of (41) and (42) gives, for an n-stage rocket and its corresponding equivalent:

$$V_к^n = c \ln \prod_{\nu=1}^{n} (1 + z_\nu) \text{ (multistage rocket)};$$

$$V_к^n = c \ln (1 + z_e) \text{ (simple rocket)},$$

from which it follows that

$$z_e = \prod_{\nu=1}^{n} (1 + z_\nu) - 1. \tag{43}$$

The coefficient z_e will be termed the reduced Tsiolkovskii coefficient for a given n-stage rocket, or the Tsiolkovskii coefficient for the equivalent rocket corresponding to it. Formula (43) shows that the limits imposed on the parameter z for an ordinary simple rocket are removed by the multistage rocket. It is evident that for an equivalent rocket z can have any numerical value; all that is necessary is to choose a sufficiently large n (the number of stages of the corresponding multistage rocket).

As an example an ordinary simple rocket and a two-stage rocket with identical weights and propellants will be compared.

Simple Rocket. $P^o = 100m$; $P^т = 79.2m$; $P^p = 1m$;

$$P^c = 19.8m.$$

and

$$z = \frac{P^т}{P^к} = \frac{79.2}{20.8} = 3.81.$$

Two-stage Rocket. $gm_1^т = 7.2\ m$; $gm_1^c = 1.8\ m$; $mg = 1\ m$ (first stage); $gm_2^т = 72\ m$; $gm_2^c = 28\ m$ (second stage)

from which

$$z_1 = \frac{m_1^т}{M_1^к} = \frac{7.2}{2.8} = 2.58;\quad z_2 = \frac{m_2^т}{M_2^к} = \frac{72}{28} = 2.58.$$

From formula (43), the parameter z_e for the equivalent rocket is:

$$z_e = (1 + к_1)\ (1 + к_2) - 1 = 11.8.$$

A two-stage rocket therefore increases the Tsiolkovskii coefficient of a simple rocket to more than three times its former value. Tsiolkovskii found this internal means of increasing rocket velocity in the design of the rocket itself. In the above example, with $c = 4000$ m/sec,

$$V_к^n = 4\,000 \ln (1 + z) = 4 \cdot 10^3 \cdot 1.6 = 6430 \text{ (simple rocket);}$$
$$V_к^n = 4\,000 \ln (1 + z_e) = 4 \cdot 10^3 \cdot 2.55 = 10\,200 \text{ (equivalent rocket).}$$

A two-stage rocket, therefore, equal in weight to a simple rocket incapable of attaining even circular velocity (8000 m/sec), can considerably exceed it.

Other kinematic and dynamic quantities characterizing the motion of a Ts^α multistage rocket will now be defined. Additional times and trajectories traversed by stages are found by using the formulas of accelerated motion:

$$\Delta\tau_i = \frac{1}{w^n}\Delta V_i = \frac{1}{\alpha_i}\ln (1 + z_i); \tag{44}$$

$$\Delta S_i = V_{i+1}\Delta\tau_i + \frac{1}{2}w\Delta\tau_i^2 = \left(V_{i+1} + \frac{1}{2}\Delta V_i\right)\Delta\tau_i. \tag{45}$$

The full flight time and corresponding trajectories of any subrocket can be found from formula (16):

$$\tau_i = \sum_{\nu=i}^{n}\Delta\tau_\nu; \tag{44'}$$

$$S_i = \sum_{\nu=i}^{n}\Delta S_\nu. \tag{45'}$$

In particular, for the first subrocket (the head rocket carrying the payload):

$$\tau_к = \sum_{\nu=1}^{n}\Delta\tau_\nu; \tag{44''}$$

$$S_{\kappa} = \sum_{\nu=1}^{n} \Delta S_{\nu}. \qquad (45")$$

Formula (44) shows that the time of engine operation is independent of the exhaust velocity c_i of the combustion products; it is proportional to the fuel supply and inversely proportional to the coefficient of fuel consumption α_i.

We now determine the jet thrust and power of rocket engines. Since the mass of the i-th subrocket changes from M_i^0 to M_i^{κ}, the thrust developed by the engines of the i-th subrocket correspondingly changes, within the limits:

$$\widetilde{R}_i^0 = \widetilde{M}_i^0 w; \ \widetilde{R}_i^{\kappa} = \widetilde{M}_i^{\kappa} w. \qquad (46)$$

The power developed by the engines of the i-th subrocket at the beginning and end of its operation is correspondingly written:

$$\widetilde{N}_i^0 = \widetilde{M}_i^0 V_{i+1} w; \ \widetilde{N}_i^{\kappa} = \widetilde{M}_i^{\kappa} V_i w. \qquad (47)$$

From these equations [(44) to (47)] it follows that only the velocities of the subrockets (ΔV_i and V_i) are independent of the jet engine rating, or, what amounts to the same thing, of the coefficient of fuel consumption α_i.

The quantities S_i and τ_i depend on α_i, i. e., on the rapidity of fuel combustion; the larger α_i, the smaller are $\Delta\tau_i$ and τ_i, ΔS_i, and S_i.

Assuming the typifying functions ψ_{τ} and ψ_c to be given, as well as the exhaust velocity c_i, the payload $\mathfrak{m}$, and m_1^c, all of the calculations for an n-stage rocket which imparts to its payload a designated terminal velocity V_{κ}^n can be carried out. In fact, (41) gives

$$V_{\kappa}^n = \ln \Pi (1 + z_i)^{c_i}$$

or

$$\prod_{\nu=1}^{n} (1 + z_{\nu})^{c_{\nu}} = e^{V_{\kappa}^n}. \qquad (48)$$

Substituting into this expression the value of z_{ν} in terms of the typifying functions (36) gives

$$\prod_{\nu=1}^{n} \left(1 + \frac{\widetilde{m}_1^{\tau} \psi_{\tau}(\nu)}{1 + \widetilde{m}_1^{\tau} \sum_{\kappa=1}^{\nu-1} \psi_{\tau}(\kappa) + \widetilde{m}_1^{c} \sum_{\kappa=1}^{\nu} \psi_c(\kappa)} \right)^{c_{\nu}} = e^{V_{\kappa}^n}. \qquad (49)$$

This equation determines m_1^{τ} and the necessary parameters for the full calculation of the multistage rocket are therefore available. The problem is simplified if the exhaust velocity is constant for all stages, $c_i = c$. In this case, (48) takes the form

$$1 + z_e = e^{\frac{V_{\kappa}^n}{c}}, \qquad (50)$$

where, by (43),

$$z_e = \prod_{\nu=1}^{n} (1 + z_{\nu}) - 1$$

or

$$z_e = \prod_{\nu=1}^{n} \left(1 + \frac{\widetilde{m}_1^{\tau} \psi_{\tau}(\nu)}{1 + \widetilde{m}_1^{\tau} \sum_{\kappa=1}^{\nu-1} \psi_{\tau}(\kappa) + \widetilde{m}_1^{c} \sum_{\kappa=1}^{\nu} \psi_c(\kappa)} \right) - 1.$$

This last equation is the solution of the problem, since z_e is determined by formula (50).

Motion of a Ts_α rocket in free space

The Ts_α and Ts^α rockets differ only in the law of combustion they follow; the former works according to the linear law

$$M_i = M_i^0 (1 - \alpha_i t), \text{ where } \alpha_i = \text{const}.$$

Since, according to Tsiolkovskii's law (39) and (40), the terminal velocity of a rocket in "free space" is independent of the law of combustion, formulas (30), (41), (48), and (50) are also applicable to Ts_α rockets.

The fuel combustion time for the i-th subrocket is found from the law of combustion:

$$\Delta\tau_i = \frac{1}{\alpha_i}\left(1 - \frac{M_i^к}{M_i^0}\right) = \frac{m_i^т}{\alpha_i M_i^0} = \frac{m_i^т}{\alpha_i (M_i^к + m_i^т)}$$

or, dividing both numerator and denominator by $M_i^к$:

$$\Delta\tau_i = \frac{z_i}{\alpha_i (1 + z_i)}; \tag{51}$$

$$\tau_i = \sum_{\nu=1}^{n} \Delta\tau_\nu. \tag{52}$$

The jet thrust is found from the law of combustion:

$$R_i = -\frac{dM_i}{dt} c_i = M_i^0 \alpha_i c_i. \tag{53}$$

From formula (53) it will be observed that the jet thrust developed by the engines of any stage does not change during the full time of operation $\Delta\tau_i$ of the engines, while the power of the engines increases from the values $R_i V_{i+1}$ to $R_i V_i$, and to the acceleration of the i-th subrocket increases in inverse proportionality to the mass of the subrocket:

$$w_i^0 = \frac{R_i}{M_i^0} = \alpha_i c_i; \tag{54}$$

$$w_i^к = \frac{R_i}{M_i^к} = \frac{M_i^0}{M_i^к} \alpha_i c_i \tag{55}$$

or, after substitution of the values of $\widetilde{M}_i^к$ from (29),

$$w_i^к = a_i c_i (1 + z_i). \tag{56}$$

As the number of the stage is increased, the numerical value of the function $\psi(i)$ increases (see formulas (31) and (32)), and the value of the Tsiolkovskii coefficient consequently decreases (see formula (36)).

From here it follows that since for the first stage $z_1 \geqslant z_i$, $w_1^к > w_i^к$. In order to limit the acceleration of the payload, therefore, the limit must be applied to $w_1^к$. Let lg, where g is the acceleration due to gravity and l, a parameter designated to indicate the acceleration of the payload, be taken as an upper limit for the possible acceleration of the payload:

$$w_1^к = \alpha_1 c_1 (1 + z_1) \leqslant lg. \tag{57}$$

From this equation the maximum accelerations are found to be:

$$\alpha_1 = \frac{lg}{c_1 (1 + z_1)}. \tag{57'}$$

Inequalities of type (57) are also observed for other stages, i.e., for any stage,

$$\alpha_i = \frac{lg}{c_i(1+z_i)}. \tag{58}$$

As far as the velocities ΔV_i and $V_к^n$ and the quantity of propellant required to attain the desired payload velocity are concerned, they can all be calculated, as has already been remarked, by formulas (39) to (41) and (48) to (50).

The trajectories followed ΔS_i are determined by formula (9):

$$\Delta S_i = V_{i+1}\Delta\tau_i + \frac{c_i}{\alpha_i}\{(1-\alpha_i\Delta\tau_i)\ln(1-\alpha_i\Delta\tau_i) + \alpha_i\Delta\tau_i\}. \tag{59}$$

The final motorized flight trajectory is determined by the summation of these paths:

$$S_к^n = \sum_{\nu=1}^{n}\Delta S_\nu. \tag{60}$$

It is evident that the motorized flight trajectories, unlike the velocities, depend on the engine operating time; they are proportional to $\Delta\tau_i$.

Motion of a Ts^a rocket in a homogeneous gravity field

It will be supposed that a multistage rocket takes off in vertical flight from the surface of the earth under the influence of the constant acceleration due to gravity and operating according to the exponential law of fuel consumption

$$M_i = M_i^0 e^{-\alpha_i t};$$

(11) then gives:

$$w = w^n - g = \alpha_i c_i - g, \tag{61}$$

where w^n is the acceleration in free space, and w (without superscript) is the acceleration of a subrocket in the gravity field. From (61) it is evident that the acceleration w in the gravity field will be constant and, consequently, that the motion will be uniformly accelerated.

The combustion law gives

$$\Delta\tau_i = \frac{1}{\alpha_i}\ln(1+z_i),$$

which is identical with (44).

The formulas for calculation of the velocities and trajectories are derived from the law of uniformly accelerated motion:

$$\Delta V_i = w\Delta\tau_i = \Delta V_i^n - g\Delta\tau_i, \tag{62}$$

where ΔV_i^n is defined by equation (39).

Further,

$$\Delta S_i = \left(V_{i+1} + \frac{1}{2}\Delta V_i\right)\Delta\tau_i = \Delta S_i^n - g\left(\tau_{i+1} + \frac{1}{2}\Delta\tau_i\right)\Delta\tau_i; \tag{63}$$

$$V_i = \sum\Delta V_\nu = V_i^n - g\tau_i; \tag{64}$$

$$S_i = \sum\Delta S_i.$$

Equations (62) and (63) show that the velocities and trajectories of rockets moving in a gravity field will be smaller than the corresponding ideal quantities (i.e., velocities and trajectories in "free space") by amounts proportional to the acceleration due to gravity.

The quantity of propellant required to achieve the desired terminal payload velocity is greater than in the case of motion in "free space."

In fact, (64) gives:

$$V_к^n = V_к + g\tau_к. \tag{65}$$

Consequently, to attain a given velocity $V_к$ in a gravity field, the ideal velocity $V_к^n$ (according to which the required fuel supply is calculated) must be increased by $g\tau_к$, i.e., by the amount of velocity lost due to gravity. In (65) the combustion time $\tau_к$ depends upon the determined fuel supply (see formulas (44) and (44")) and can therefore be expressed in terms of given quantities. By the law of uniformly accelerated motion,

$$V_к = w\tau_к.$$

Consequently,

$$V_к^n = V_к \frac{w^n}{w}. \tag{66}$$

Let the maximum possible acceleration be lg, where l is a given quantity. Then

$$V_к^n = V_к \frac{1+l}{l}. \tag{67}$$

Substituting this expression for $V_к^n$ in equation (49) gives a working formula for the determination of $\widetilde{m}_i^т$ and, consequently, of the fuel supply $\widetilde{M}_i^т$ (see equation (35)), required to attain the given velocity $V_к$ in the gravity field. As an example, if the payload is an artificial satellite driven along a given orbit by a multistage rocket, $V_к \approx 8000$ m/sec.

Motion of a Ts_a rocket in a homogeneous gravity field

The Tsiolkovskii-Meshcherskii Equation (II) gives, for the i-th subrocket,

$$M_i w_i = R_i - M_i g$$

or

$$w_i = w_i^n - g. \tag{68}$$

from which

$$\Delta V_i = \Delta V_i^n - g\Delta\tau_i;$$
$$\Delta S_i = \Delta S_i^n - \frac{1}{2} g\Delta\tau_i^2;$$
$$V_i = V_i^n - g\tau_i;$$
$$S_i = S_i^n - \frac{1}{2} g \sum_{\nu=1}^{n} \Delta\tau_\nu^2.$$

Limiting the terminal acceleration of the subrockets here, as above, to the maximum value permitted by physiological and engineering limitations lg (where l is a given quantity) gives the following ratio, analogous to (58), for α_i:

$$\alpha_i = \frac{(l+1)g}{c_i(1+z_i)}. \tag{69}$$

The quantity of propellant required to reach the set payload velocity $V_к$ is determined as follows.

By (51) and (69),

$$\tau_к = \frac{1}{g(l+1)} \sum_{i=1}^{n} c_i z_i.$$

Substituting this value of $\tau_к$ in the equation $V_к^n = V_к + g\tau_к$ gives

$$V_к^n = V_к + \frac{1}{l+1} \sum_{i=1}^{n} c_i z_i.$$

Finally, substituting into this equation the expression for $V_к^n$ from (40) and the expression for the Tsiolkovskii coefficient z_i from (36) gives a working formula for the determination of $\widetilde{m}_1^т$ and, consequently, of $\widetilde{M}_n^т$, for a given multistage rocket Ts_a, moving in a gravity field:

$$\prod \left(1 + \frac{\widetilde{m}_1^т \psi_т(\nu)}{1 + \widetilde{m}_1^т \sum_{к=1}^{\nu-1} \psi_т(к) + \widetilde{m}_1^c \sum_{к=1}^{\nu} \psi_c(к)} \right)^{c_\nu} =$$

$$= V_к + \frac{1}{g(l+1)} \sum c_\nu \frac{\widetilde{m}_1^т \psi_т(\nu)}{1 + \widetilde{m}_1^т \sum_{к=1}^{\nu-1} \psi_т(к) + \widetilde{m}_1^c \sum_{к=1}^{\nu} \psi_c(к)}$$

ACTUAL TYPES OF MULTISTAGE TSIOLKOVSKII ROCKETS

The theory of generalized multistage Tsiolkovskii rockets (Ts) is developed above. The actual Tsiolkovskii rockets described by him in his work "Kosmicheskie raketnye poezda" (Cosmic Rocket Trains) and designated by him with the letters A, B, C, and D are, as it is proposed to show, special cases of these. Tsiolkovskii's outmoded terms "rocket train" and "partial rocket train" will be replaced throughout by the corresponding contemporary terms "multistage rocket" and "subrocket!" Tsiolkovskii studied three of the rocket types, A, B, and D, in detail, illustrating their special features and performing numerical calculations which he collected in tables. Although he considered type C the best, he did not, as he himself wrote, investigate it so thoroughly. The theory of these rockets will be presented here only from the point of view of generalized Tsiolkovskii rockets (Ts). To do this it is necessary only to establish, by the use of the characteristics of rockets A, B, C, and D, set forth by Tsiolkovskii in his paper, a special form of the typifying functions $\psi_т$ and ψ_c.

General characteristics of multistage Tsiolkovskii rockets A and D

Tsiolkovskii outlined the characteristic properties of type A rockets as follows:

"The rockets (stages are meant - V. K.) are constructed almost identically. The supply of explosive is practically the same, but the greater the mass of the train, the more powerful is the explosion. Because of this all the

partial trains (i.e., subrockets — V. K.) have the same acceleration, but the explosion time is inversely proportional to the mass of the train (subrocket — V. K.)."*

The same characteristics of type A rockets are given elsewhere: "But here we suppose the velocity and force of the explosion of one and the same mass of explosive to be proportional to the mass of the train. Then the first train of, let us say, five rockets, will be pulled by a force five times greater than in the case of one rocket, and both trains therefore have the same acceleration, as well as all partial trains of one general train. The result is that, regardless of the different numbers of rockets in different trains, it is as if we had one body moving with constant acceleration. However, the time of explosion is of course inversely proportional to the masses of the partial trains (or, the more powerful the explosion, the sooner it is completed)."**

The characteristics cited thus make it clear that the dry masses and fuel supplies of all the stages were identical or "almost identical." Consequently,

$$m_i^c = m_1^c; \quad m_i^\tau = m_1^\tau.$$

Comparison of this equality with equalities (30) and (31) gives

$$\psi_c(i) = \psi_\tau(i) = 1.$$

The type A rocket is therefore a very simple form of the generalized Tsiolkovskii multistage rocket: its typifying functions are identical, i.e., $\psi_\tau(i) = \psi_c(i)$ and both have a very simple constant numerical value, unity. Tsiolkovskii wrote, with reference to these and type D rockets, "We shall first solve the problem in the most simple form."†

Now that the type A multistage rocket has been defined, some of its other characteristics can be considered. Tsiolkovskii wrote: "the greater the mass of the train, the more powerful is the explosion," and "the velocity and force of the explosion of one and the same mass of explosive [are supposed] to be proportional to the mass of the train." If this proportionality between the velocity of mass change of the i-th subrocket and its mass is written down,

$$\frac{dM_i}{dt} = -\alpha_i M_i,$$

where α_i is a coefficient of proportionality. Integrating this differential equation gives

$$M_i = M_i^0 e^{-\alpha_i t}.$$

This means that the subrockets of the type A train obey the exponential law and therefore have constant acceleration (see formulas (38) and (4))

$$w = \alpha_i c_i.$$

Since Tsiolkovskii took the exhaust velocities c_i to be identical for all subrockets ($c_i = c$), it follows from the law of acceleration that the coefficients α_i are also identical for all subrockets, i.e., $\alpha_i = \alpha$.

Giving the characteristics of type A rockets their mathematical expression, they can finally be written in the form:

$$\psi_\tau(i) = 1; \quad \psi_c(i) = 1; \quad M_i = M_i^0 e^{-\alpha t}. \tag{70}$$

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.321.

** Ibid., p.311.

† Ibid., p.300.

These characteristics, together with the parameters m_1^{τ}, m_1^{c}, and $\mathfrak{m}$, of the first subrocket permit full calculation of the masses of all stages and subrockets, as well as calculation of the fundamental characteristics of the rocket motion.

Type D multistage Tsiolkovskii rockets belong to the same category as type A rockets. Tsiolkovskii wrote about them: "All of the rockets (stages are meant— V. K.) are completely identical as far as fuel supply and character of explosion are concerned. The greater the mass of the partial train (i. e., subrocket— V. K.), the less is the acceleration. All of the trains (subrockets— V. K.) have the same time of explosion."*

In another place, referring to type D rockets, he wrote "Let all the rockets be supposed completely identical with regard to structure, as well as fuel supply and character of the explosive force."**

The foregoing characteristics yield, as for A rockets:

$$m_i^{\tau} = m_1^{\tau}; \quad m_i^{c} = m_1^{c}.$$

The typifying functions of D rockets are therefore represented by law (70), and as a result A and D rockets belong to the same category. It has been shown further that the stages of type D rockets are "identical with regard to the character of the explosive force," a feature mathematically representable in the two equivalent forms

$$R_i = r\,(\text{const}) \text{ or } \frac{dM_i}{dt} = b\,(\text{const}).$$

Taking the first of these, since Tsiolkovskii directly mentions a constant explosive force, gives

$$R_i = -\frac{dM_i}{dt}c = r.$$

and by integration,

$$M_i = M_i^0(1 - \alpha_i t), \text{ where } \alpha_i = \frac{r}{M_i^0 c}.$$

Rocket D is therefore identical to rocket A, but if A operates according to the exponential law (with uniform acceleration), D follows the linear law (with constant jet thrust).

The period of engine operation for any i-th subrocket of an A or D rocket, i. e., the fuel combustion time $\Delta\tau_i$ for the i-th stage, will now be found.

The motion of rocket A follows law (70). At the end of combustion, $M_i^{\kappa} = M_i^0 e^{-\alpha\Delta\tau_i}$ or $\alpha\Delta\tau_i = \ln\frac{M_i^0}{M_i^{\kappa}}$, and finally

$$\Delta\tau_i = \frac{1}{\alpha}\ln(1 + z_i). \tag{72}$$

For large values of the subscript i, i. e., for small values of z_i ($z_i \ll 1$), taking only the first term of the series expansion of $\ln(1 + z_i)$ gives

$$\Delta\tau_i = \frac{1}{\alpha}z_i = \frac{m_1^{\tau}}{\alpha M_i^{\kappa}}.$$

* Ibid., p. 321.

** Ibid., p. 300.

This equation shows that Tsiolkovskii was right in stating that for rocket A "the explosion time (i.e., $\Delta\tau_i$) is inversely proportional to the mass of the train." The motion of rocket D follows law (71). At the termination of combustion,

$$M_i^к = M_i^0(1 - \alpha_i\Delta\tau_i)$$

or

$$\Delta\tau_i = 1 - \frac{M_i^к}{M_i^0}\frac{m_1^т}{\alpha_i M_i^0}.$$

Substituting in this equation the value of α_i from (71) gives

$$\Delta\tau_i = \frac{m_1^т}{r}c. \qquad (73)$$

Equation (73) confirms Tsiolkovskii's other conclusion that "all of the trains have the same time of explosion."

Independent characteristic coefficients and masses of A and D multistage rockets

Since A and D belong to the same category their independent characteristic coefficients z_i and s_i and the masses of their stages and subrockets will be identically expressed.

Substituting in (36) and (37) the specific form of the A and D typifying functions gives:

$$z_i = \frac{\widetilde{m}_1^т}{1 + i\widetilde{m}_1^c + (i-1)\widetilde{m}_1^т};$$

$$s_i = 1 + \frac{\widetilde{m}_1^т}{\widetilde{m}_1^c} = s.$$

It is evident that the Tsiolkovskii number z_i for A and D rockets decreases rapidly from the first to the last subrocket, while the structural coefficients of all stages have one and the same value. The masses are therefore easily calculated. By equation (33),

$$\widetilde{M}_i^0 = 1 + i\widetilde{m}_1^т + i\widetilde{m}_1^c,$$

and by equation (35),

$$\widetilde{M}_i^т = i\widetilde{m}_1^т; \quad \widetilde{M}_i^c = i\widetilde{m}_1^c.$$

Motion of A and D Tsiolkovskii rockets in free space

It should be observed that A rockets belong to the Ts^{α} class of generalized Tsiolkovskii rockets, whose motion follows the exponential law of fuel combustion, while D rockets belong to the Ts_{α} class, which follow the linear law. All of their kinematic and dynamic characteristics are therefore determined by the formulas introduced above. Tables 1 and 2 (below) have been compiled respectively for A and D rockets.

General characteristics of B and C multistage Tsiolkovskii rockets

Tsiolkovskii defined the characteristic properties of B rockets as follows: "The greater the mass of the partial train (subrocket – V. K.), the greater is the supply of explosive and the explosive force. For this reason acceleration and explosion time are identical for all the trains."* Elsewhere, with reference to these rockets, Tsiolkovskii wrote, "For trains of 2, 3, and 4 rockets (i. e., for low-order multistage rockets), not only the acceleration may be supposed constant, but the time of explosion can also be considered invariant. For this to be so, however, the fuel supply in each driving rocket must be proportional to the explosive force or to the mass of each partial train... Here too all the partial trains move as a single body with constant acceleration."**

Let it be remarked at the outset that B and C rockets belong to the same category, since they obey the same law of mass distribution. In fact, referring to C rockets, Tsiolkovskii wrote:

"The supply of explosive is proportional to the mass of the partial train (as for B rockets – V. K.), but the explosive force is constant."† As is evident from the characteristics cited, B and C rockets belong to the same category, but different classes.

That B and C rockets belong to a common category, i. e., obey the same law of mass distribution, also follows from a hint given by Tsiolkovskii: "Although we have not analyzed this case (i. e., the case of C rockets – V. K.), Table 66 can be used for them with regard to the magnitude of the additional velocities."†† Tsiolkovskii compiled the tables here mentioned for B rockets, and therefore, in remarking on their suitability for C rockets, he placed B and C rockets in the same category.

B rockets move with uniform acceleration, that is, they belong to class Ts^{a}, and C rockets move with constant thrust, that is, they obey the linear law of fuel consumption and therefore belong to class Ts_{a}.

Determination of the typifying functions for B and C rockets, which are interrelated like A and D rockets, will now be taken up.

Tsiolkovskii wrote, "the supply of explosive is proportional to the mass of the partial train," therefore,

$$m_i^{\tau} = \lambda M_i^{\kappa},$$

where λ is the coefficient of proportionality.

Tsiolkovskii does not say anything definite about the law of increase of the dry masses m_i^{c}, but it is clear that they must also increase. He wrote, "System B requires the greater increase in the mass and volume of the rocket, the more elements there are in the train. Room must be found for fuel, as well as more complicated and powerful engines."‡ From this it follows that the dry mass must increase with the number i of the stage. Of course, the form of $\psi_c(i)$ may still be arbitrarily chosen. Here the law of

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol.II, p.321.
** Ibid., pp.314, 316.
† Ibid., p.321.
†† Ibid., p.322.
‡ Ibid., p.321

increase of the dry mass will be put in the form

$$m_i^c = \rho^{i-1} m_i^c, \tag{75}$$

where ρ is a still unspecified constant to be determined later.

Comparison of (75) with (19) gives

$$z_i = \lambda, \text{ i.e., } z_i = z_2 = \ldots = z_n = z.$$

Using (74) and (75), the initial masses of the consecutive subrockets can now be written down:

$$\begin{aligned}
&M_1^0 = m_1^T + m_1^c = \mathfrak{m};\\
&M_2^0 = m_2^T + m_2^c + M_1^0 = M_1^0 + zM_2^K + \rho m_1^c = (z+1) M_1^0 + \rho (z+1) m_1^c;\\
&M_3^0 = \ldots = (z+1)^2 M_1^0 + \rho (z+1) \{\rho + z + 1\} m_1^c;\\
&M_4^0 = \ldots = (z+1)^3 M_1^0 + \rho (z+1) \{(z+1)^2 + \rho (z+1) + \rho^2\} m_1^c;\\
&M_5^0 = \ldots = (z+1)^4 M_1^0 + \rho (z+1) \{(z+1)^3 + \rho (z+1)^2 + \\
&\qquad + \rho^2 (z+1) + \rho^3\} m_1^c,
\end{aligned}$$

etc.

$$\begin{aligned}
M_i^0 = (z+1)^{i-1} M_1^0 + \rho (z+1) \{&(z+1)^{i-2} + \rho (z+1)^{i-3} + \\
+ \rho^2 (z+1)^{i-4} + \ldots + \rho^{K-1} (z+1)^{i-(K+1)} + \ldots + \rho^{i-4} (z+1)^2 + \\
&+ \rho^{i-3} (z+1) + \rho^{i-2}\} m_1^c.
\end{aligned}$$

Since the braces contain the sum of the members of a geometrical progression with denominator $\rho (z+1)^{-1}$,

$$M_i^0 = (z+1)^{i-1} M_1^0 + \rho (z+1) \frac{(z+1)^{i+1} - \rho^{i-1}}{(z+1) - \rho} m_1^c.$$

Substituting into this equation

$$m_1^c = \tilde{m}_1^c \mathfrak{m} \quad \text{and} \quad M_1^0 = (z+1)(\tilde{m}_1^c + 1)\mathfrak{m},$$

gives

$$M_i^0 = \left[(z+1)^{i-1} (1 + \tilde{m}_1^c) + \rho \frac{(z+1)^{i-1} - \rho^{i-1}}{(z+1) - \rho} \tilde{m}_1^c \right] (z+1) \mathfrak{m}.$$

By (27)

$$\tilde{m}_i^T = \frac{z}{1+z} \tilde{M}_i^0$$

or, substituting in this equation the value found for M_i^0,

$$\tilde{m}_i^T = \left[(z+1)^{i-1} (\tilde{m}_1^c + 1) + \tilde{m}_1^c \rho \frac{(z+1)^{i-1} - \rho^{i-1}}{(z+1) - \rho} \right] \frac{\tilde{m}_1^T}{1 + \tilde{m}_1^c}.$$

Putting

$$z + 1 = r, \qquad \frac{\rho \tilde{m}_1^c}{1 + \tilde{m}_1^c} = a, \tag{76}$$

we obtain finally (see formula (30))

$$\tilde{m}_i^T = \psi_T (i) \tilde{m}_1^T,$$

where

$$\psi_T (i) = r^{i-1} + a \frac{r^{i-1} + \rho^{i-1}}{r - \rho}$$

The second typifying function $\psi_c (i)$ is found from the comparison of (75) and (30):

$$\psi_c (i) = \rho^{i-1}.$$

B and C Tsiolkovskii rockets therefore belong to a single category and have the typifying functions:

$$\psi_{\tau}(i) = r^{i-1} + a\frac{r^{i-1} - \rho^{i-1}}{r - \rho}; \tag{77}$$

$$\psi_{c}(i) = \rho^{i-1}, \tag{78}$$

where the constants r and a are defined by (76). The characteristic coefficients z_i, s_i, p_i, and P cannot have arbitrary numerical values, but are limited to what engineering techniques will allow. For example, P is taken as < 500. These limiting values of s_i, p_i, or P permit determination of the parameter ρ. Its numerical value can also be determined by taking the minimum of the coefficient P. By (23), in fact,

$$P = \frac{M_n^0}{m} = M_n^0.$$

and by (27),

$$\widetilde{M}_n^0 = P = \frac{1+z}{z} m_n^{\tau}$$

or by (30),

$$P = \frac{r}{r-1}\psi_{\tau}(n)\,\widetilde{m}_1^{\tau},$$

or by (77),

$$P = \frac{r}{r-1}\left[r^{n-1} + a\frac{r^{n-1} - \rho^{n-1}}{r-\rho}\right]\widetilde{m}_1^{\tau}. \tag{79}$$

If the given m_1^{τ}, m_1^{c}, and $\mathfrak{m}$, and with them the coefficients a and r, are taken as parameters of the first subrocket,

$$P = f(\rho).$$

Solving for the minimum of P leads to determination of the corresponding optimum value of ρ.

After determination of the typifying functions and choice of the working parameters $\widetilde{m}_1^{c}$ and $\widetilde{m}_1^{\tau}$, a full calculation (in dimensionless quantities) of B and C rockets can be carried out by the method presented above for generalized Ts^{α} and Ts_{α} Tsiolkovskii rockets.

It will readily be seen that the category here established for B and C rockets, (77) and (78), corresponds precisely with the characteristics established for them by Tsiolkovskii.

If, following Tsiolkovskii, c and α are taken as the same for all stages of a B rocket, (38) gives

$$w_i = w = \alpha c. \tag{80}$$

Formulas (39), (41), (44), and (44") then take the appearance:

$$\Delta V_i = c\ln(1+z); \tag{81}$$

$$V_{\kappa} = cn\ln(1+z); \tag{82}$$

$$\Delta\tau_i = \frac{1}{\alpha}\ln(1+z); \tag{83}$$

$$\tau_{\kappa} = \frac{n}{\alpha}\ln(1+z). \tag{84}$$

All of these formulas confirm the characteristics given by Tsiolkovskii for B rockets.*

* Tsiolkovskii, K.E. "Sobranie sochinenii" (Collected Works), Vol. II, pp. 314, 321.

The mass and velocity characteristics of C rockets in free space will all coincide with the corresponding characteristics of B rockets, since they both belong to the same category. The characteristics related to acceleration and time, however, will be essentially different as a result of the difference in fuel combustion laws.

The calculation of C rockets is carried out as shown above. Following Tsiolkovskii, the jet thrust is taken to be identical for all stages, and equal to r. Equation (53) then gives:

$$R_i = c\alpha_i M_i^0 = r. \tag{85}$$

Once r is determined, α_i can thus be found:

$$\alpha_i = \frac{r}{cM_i^0}, \tag{86}$$

that is, the coefficients of fuel consumption α are different for different stages, and for each stage the acceleration is inversely proportional to the mass of the subrocket. By (54) and (55):

$$w_i^0 = \frac{r}{M_i^0}; \quad w_i^K = \frac{r}{M_i^K}. \tag{87}$$

These relationships determine the value of r through the limiting conditions for permissible accelerations.

The period of engine operation of the i-th stage is found from (51):

$$\Delta\tau_i = \frac{z}{(1+z)\alpha_i} = \frac{cz}{r(1+z)} M_i^0. \tag{88}$$

Formulas (85), (86), and (88) fully confirm all of the C rocket characteristics given by Tsiolkovskii.*

Tables 3 and 4 (below) have been compiled respectively for B and C rockets.

EXAMPLES OF GENERALIZED MULTISTAGE TSIOLKOVSKII ROCKETS

Multistage rockets with different characteristics can be obtained by choice of the typifying functions ψ. Some actual examples of the structure of Ts rockets will now be considered.

Type G multistage rockets

Assume that the masses of stages increase in arithmetic progression:

$$m_i^\tau = im_1^\tau; \quad m_i^c = im_1^c.$$

The typifying functions are then assumed to have the form

$$\psi_\tau(i) = \psi_c(i) = i.$$

* Ibid., pp. 321, 322.

As was show above, the masses of the stages of the rocket can be fully calculated if the forms of the typifying functions and the parameters of the first subrocket $m_1^т$, m_1^c, and m are known. The special feature of the G rocket is that its structural coefficients s_i are equal for all stages:

$$s_i = s = \frac{m_1^0}{m_1^c} = 1 + \frac{m_1^т}{m_1^c}.$$

The coefficients z_i are of course dependent on the subscript:

$$z_i = \frac{im_1^т}{m + m_1^т \frac{(i-1)i}{2} + m_1^c \frac{(i+1)i}{2}}.$$

The results of calculations for G rockets are given in Tables 5 and 6 (see below).

The typifying functions representing the general law of increase of the masses of a multistage rocket in arithmetic progression, with identical structural coefficients for all stages, have the form:

$$\psi_т(i) = \psi_c(i) = 1 + c(i-1).$$

The Tsiolkovskii coefficients z_i can be influenced by choice of the constant c.

In particular, a G rocket is obtained if $c = 1$; A and D Tsiolkovskii rockets are obtained if $c = 0$.

Type E multistage rockets

Now assume that the masses of stages increase in geometric progression:

$$m_i^т = c^{i-1} m_1^т; \quad m_i^c = c^{i-1} m_1^c.$$

The typifying functions are then assumed to have the form:

$$\psi_т(i) = \psi_c(i) = c^{i-1}.$$

These rockets also have identical structural coefficients s_i for all stages. The Tsiolkovskii coefficients z_i are dependent upon the subrocket subscript i:

$$z_i = \frac{c^{i-1} m_1^т}{m + m_1^т \frac{c^{i-1}-1}{c-1} + m_1^c \frac{c^i - 1}{c-1}}.$$

As the formula shows, they decrease with increase of the subscript i.

For any c, the coefficients s_i have identical numerical values independent of c and determined by the values of the working parameters $m_1^т$ and m_1^c:

$$s_i = \frac{m_i^0}{m_i^c} = \frac{m_1^0}{m_1^c} = s_1.$$

The coefficients z_i, however, can also be made independent of i through the choice of c:

$$z_i = \frac{\widetilde{m}_i^т}{\widetilde{M}_i^к} = \frac{\widetilde{m}_i^т}{\widetilde{M}_i^0 - \widetilde{m}_i^т}.$$

If it is noticed that for the E rockets under consideration,

$$\widetilde{m}_i^т = c^{i-1} \widetilde{m}_1^т,$$

this object can be attained by representing $\widetilde{M}_i^0$ in the form $c^i A$ or $c^{i-1} A$,

where A is a coefficient independent of the subscript i. By (33),

$$\widetilde{M}_i^0 = 1 + \frac{c^i - 1}{c - 1}\,\widetilde{m}_1^0 = \frac{(c-1) + c^i\widetilde{m}_1^0 - \widetilde{m}_1^0}{c-1}.$$

To solve the problem it is now sufficient to put

$$c = \widetilde{m}_1^0 + 1.$$

which gives, from the above,

$$\widetilde{M}_i^0 = c^i.$$

Consequently,

$$z_i = \frac{\widetilde{m}_i^\tau}{\widetilde{M}_i^0 - \widetilde{m}_i^\tau} = \frac{c^{i-1}\widetilde{m}_1^\tau}{c^i - c^{i-1}\widetilde{m}_1^\tau} = \frac{\widetilde{m}_i^\tau}{\widetilde{m}_i^c + 1} = \frac{\widetilde{m}_1^\tau}{m_1^c + \mathfrak{m}} = z_1;$$

$$z_i = z_1.$$

E rockets with $c = \widetilde{m}_1^0 + 1$, i.e., $z_i = z_1$, will be designated by the letter $\mathscr{E}$. The results of numerical calculations for $\mathscr{E}$ rockets are given in Tables 7 and 8 (see below).

For $c = 1$, E rockets become A and D rockets.

Explanation of tables

Tables 1, 3, 5, and 7 are for multistage rockets of class Ts^α; they fly with constant acceleration, identical for all subrockets, and the engines of all stages therefore obey the exponential law of fuel consumption. Tables 2, 4, 6, and 8 are for rockets of class Ts_λ; they fly with a constant thrust, identical for all subrockets, and the engines of all stages therefore obey the linear law of fuel consumption.

At the beginning of all the tables the number of stages and subrockets i and the number n, designating the order of the multistage rocket, are indicated.

The i-subscripted quantities refer to the i-th subrocket or stage. For example, m_i^c (see line 2 of the odd-numbered tables) is the dimensionless dry mass of the i-th stage; M_i^c (line 4 of the odd-numbered tables) is the dimensionless dry mass of the corresponding i-th subrocket. Their numerical values, for the third stage or subrocket, for instance, will be found in the column for $i = 3$.

Dimensionless masses and other quantities marked above with a wavy line indicate the ratio of the corresponding quantities to the payload mass $\mathfrak{m}$; for example, $\widetilde{M}_i^0 = M_i^0 : \mathfrak{m}$, $\widetilde{R}_i = R_i : \mathfrak{m}$.

All of the tables have been compiled for rocket motion in "free space," and for identical working parameters, and as a result, the first eleven lines are identical for the corresponding odd- and even-numbered tables, compiled for rockets of the same type, i.e., having the same typifying functions, such as A and D, B and C, etc.

The identical first eleven lines are therefore not repeated in the even-numbered tables. This means that for rockets of Class G_λ, lines 1 to 11 (masses, characteristic coefficients, and velocities) can be taken without changes from Table 5, compiled for rockets of type G^α, etc. Above each

TABLE 1

For A^{α}

	i, n	5	4	3	2	1
1	$\widetilde{m}_i^{\tau}$	12	12	12	12	12
2	$\widetilde{m}_i^{c}$	3	3	3	3	3
3	$\widetilde{M}_i^{\tau}$	60	48	36	24	12
4	$\widetilde{M}_i^{c}$	15	12	9	6	3
5	$\widetilde{M}_i^{o}$	76	61	46	31	16
6	M_i^{κ}	64	49	34	19	4
7	z_i	0.188	0.245	0.353	0.632	3
8	s_i	5	5	5	5	5
9	z_n^{e}	12.1	9.99	7.83	5.53	3
10	$\Delta V_i : c$	0.172	0.219	0.302	0.490	1.386
11	$V_n^{\kappa} : c$	1.1173	1.0410	0.9460	0.8149	0.6021
12	$w : c = \alpha_i$	0.01	0.01	0.01	0.01	0.01
13	$\Delta\tau_i$	17.2	21.9	30.2	49.0	138.6
14	τ_n^{κ}	111.7	104.1	94.6	81.49	60.21
15	$\widetilde{R}_i : c$	0.76	0.61	0.46	0.31	0.16

TABLE 2

For D_{α}

	i, n	5	4	3	2	1
12*	$c\,\alpha_i$	2.102	2.625	3.48	5.16	10
13	$\Delta\tau_i : c$	0.075	0.075	0.075	0.075	0.075
14	$\tau_n^{\kappa} : c$	0.375	0.300	0.225	0.15	0.075
15	w_i^{o}	2.102	2.625	3.48	5.16	10
16	w_i^{κ}	2.5	3.27	4.71	8.2	40
17	$\widetilde{R}_i$	160	160	160	160	160

* The values of items 1 to 11 are as in Table 1.

TABLE 3

For B^{α}

	i, n	5	4	3	2	1
1	$\widetilde{m}_i^{\tau}$	$105\cdot10^{3}$	11500	1250	129	12
2	$\widetilde{m}_i^{c}$	19700	2190	243	27	3
3	$\widetilde{M}_i^{\tau}$	$118\cdot10^{3}$	12900	1390	141	12
4	$\widetilde{M}_i^{c}$	22100	2460	273	30	3
5	$\widetilde{M}_i^{o}$	$14\cdot10^{4}$	15400	1660	172	16
6	$\widetilde{M}_i^{\kappa}$	35100	3850	415	43	4
7	z_i	3	3	3	3	3
8	s_i	6,35	6.28	6.12	5.78	5
9	z_n^{e}	1023	255	63	15	3
10	$\Delta V_i : c$	1.39	1.39	1.39	1.39	1.39
11	$V_n^{\kappa} : c$	3.0103	2.4082	1.8062	1.2041	0.6021
12	$w.c = \alpha_i$	0.01	0.01	0.01	0.01	0.01
13	$\Delta\tau_i$	139	139	139	139	139
14	τ_n^{κ}	301.03	240.82	180.62	120.41	60.21
15	$\widetilde{R}_i : c$	$14\cdot10^{3}$	154	16.6	1.72	0.16

TABLE 4

For C_{α}

	i, n	5	4	3	2	1
12*	$c\cdot\alpha_i$	$114\cdot10^{-5}$	$104\cdot10^{-4}$	$964\cdot10^{-4}$	0.93	10
13	$\Delta\tau_i : c$	656.25	72.19	7 78	0.806	0.075
14	$\tau_n^{\kappa} : c$	737.1	80.85	8.661	0.881	0 075
15	w_i^{o}	$114\cdot10^{-5}$	$104\cdot10^{-4}$	$964\cdot10^{-4}$	0.93	10
16	w_i^{κ}	$456\cdot10^{-5}$	$416\cdot10^{-4}$	$386\cdot10^{-3}$	$372\cdot10^{-2}$	40
17	$\widetilde{R}_i$	160	160	160	160	160

* The values of items 1 to 11 are as in Table 3.

TABLE 5

For G^{α}

	i, n	5	4	3	2	1
1	$\widetilde{m}_i^{\tau}$	60	48	36	24	12
2	$\widetilde{m}_i^{c}$	15	12	9	6	3
3	$\widetilde{M}_i^{\tau}$	180	120	72	36	12
4	$\widetilde{M}_i^{c}$	45	30	18	9	3
5	$\widetilde{M}_i^{o}$	226	151	91	46	16
6	$\widetilde{M}_i^{\kappa}$	166	103	55	22	4
7	z_i	0.361	0.466	0.654	1.09	3
8	s_i	5	5	5	5	5
9	z_n^{e}	26,6	19.3	12.8	7.36	3
10	$\Delta V_i : c$	0.309	0.389	0.504	0.718	1.39
11	$V_n^{\kappa} : c$	1.4409	1.3075	1.1399	0.9222	0.6021
12	$w : c = \alpha_i$	0.01	0.01	0.01	0.01	0.01
13	$\Delta\tau_i$	30.9	38.9	50.4	71.8	139
14	τ_n^{κ}	144.09	130.75	113.99	92.22	60.21
15	$\widetilde{R}_i : c$	2.26	1.51	0.91	0.46	0.16

TABLE 6

For G_{α}

	i, n	5	4	3	2	1
12*	$c \cdot \alpha_i$	0.709	1.06	1.76	3.48	10
13	$\Delta\tau_i : c$	0.375	0.3	0.225	0.15	0.075
14	$\tau_n^{\kappa} : c$	1.125	0.75	0.45	0.225	0.075
15	w_i^{o}	0.709	1.06	1.76	3.48	10
16	w_i^{κ}	0.964	1.553	2.915	7.275	40
17	$\widetilde{R}_i$	160	160	160	160	160

* The values of items 1 to 11 are as in Table 5.

TABLE 7

For E^{α}

	i, n	5	4	3	2	1
1	$\widetilde{m}_i^{\tau}$	$786 \cdot 10^3$	49100	3070	192	12
2	$\widetilde{m}_i^{c}$	$197 \cdot 10^3$	12300	768	48	3
3	$\widetilde{M}_i^{\tau}$	$839 \cdot 10^3$	52400	3280	204	12
4	$\widetilde{M}_i^{c}$	$21 \cdot 10^4$	13100	819	51	3
5	$\widetilde{M}_i^{o}$	$105 \cdot 10^4$	65500	4100	256	16
6	M_i^{κ}	$262 \cdot 10^3$	16400	1020	64	4
7	z_i	3	3	3	3	3
8	s_i	5	5	5	5	5
9	z_n^{e}	1023	255	63	15	3
10	$\Delta V_i : c$	1.39	1.39	1.39	1.39	1.39
11	$V_n^{\kappa} : c$	3.0103	2.4082	1.8062	1.2041	0.6021
12	$w : c = \alpha_i$	0.01	0.01	0.01	0.01	0.01
13	$\Delta\tau_i$	139	139	139	139	139
14	τ_n^{κ}	301.03	240.82	180.62	120.41	60.21
15	$\widetilde{R} : c$	$105 \cdot 10^3$	655	41	2.56	0.16

Table 8

For E_{α}

	i, n	5	4	3	2	1
12*	$c \cdot \alpha_i$	$152 \cdot 10^{-6}$	$244 \cdot 10^{-5}$	0.0391	0.626	10
13	$\Delta\tau_i : c$	4915.2	307.2	19.2	1.2	0.075
14	$\tau_n^{\kappa} : c$	5242.87	327.675	20.475	1.275	0.075
15	w_i^{o}	$152 \cdot 10^{-6}$	$244 \cdot 10^{-5}$	0.0391	0.626	10
16	w_i^{κ}	$612 \cdot 10^{-6}$	$977 \cdot 10^{-5}$	0.1567	2.5	40
17	$\widetilde{R}_i$	160	160	160	160	160

* The values of items 1 to 11 are as in Table 7.

table are indicated the typifying functions determining the type of multistage rocket under consideration.*

The n-subscripted quantities refer to the order, not of subrocket or stage (which are designated by the subscript i), but of a corresponding multistage rocket (taken as a whole) of order n.

For example, $V_n^к$, $\tau_n^к$ and z_n^e designate the terminal velocity, full motorized flight time, and reduced Tsiolkovskii coefficient for a multistage rocket of order n. Five stages are covered in the tables. A multistage rocket of order 5 is meant by $n=5$, while $n=3$ indicates a three-stage rocket rocket, for which $i=3, 2, 1$, etc. Table 7, for example, shows that a three-stage E^a rocket ($n=3$) communicates to its payload a terminal velocity of 4.17c.

This means that for $c=2000$ m/sec, the payload will attain a velocity of 8340 m/sec, above circular velocity; for $c=3000$ m/sec, the payload velocity will be 12,510 m/sec, and will exceed escape velocity; for $c=4000$ m/sec, the payload velocity will be 16,680 m/sec. Table 3 shows that the same results can be obtained with a three-stage Tsiolkovskii B rocket.

Comparison of Tables 3 and 7 shows the great superiority of B to E rockets. E rockets have a launching weight per unit of payload almost 2 1/2 times that of B rockets, and must therefore develop a considerably greater thrust, which requires heavier and more complicated engines.

All of the odd-numbered tables, referring to Ts^a rockets, have been calculated for $a=0.01$. This value of a results from the requirement that the g-load should not exceed the physiologically permissible value, here taken as equal to 4, which corresponds to the highest practically attainable exhaust velocities $c=4000$ m/sec. All of the even-numbered tables have been computed for the same thrust $\tilde{R}=160$. This value for the reactive force follows from the requirement that the maximum acceleration (which is the terminal acceleration $w_1^к$ of the last stage) not exceed physiologically permissible g-loads, i.e., $w_1^к = 4$ g, for the maximum exhaust velocity $c=4000$ m/sec.

Summarizing table

For comparative analysis I have compiled a summary table, which will permit a, so to speak, "dimensionless" evaluation of A, B, C, and D multistage Tsiolkovskii rockets, by comparing them with several actual or projected contemporary multistage rockets whose data are available in print.

The summary table clearly shows the efficiency of B and C Tsiolkovskii rockets. These rockets are in all respects the equal of the contemporary foreign multistage rocket designs presented in the table. They have the highest reduced Tsiolkovskii coefficient z^e and, consequently, the highest ideal terminal velocity ($V^к : c=4.2$). It should be mentioned that the values of the characteristic coefficients z_i and s_i, and the launching weight per unit of payload $\tilde{P}^0$, of Tsiolkovskii rockets, are in practice allowable.

* [The typifying functions mentioned here do not in fact appear above the tables in the printed text, and are to be found only in the preceding sections of the paper, where they are mathematically derived.]

Comparing the characteristic data of generalized E and actual B and C types of Tsiolkovskii rockets shows the pronounced influence of the characteristic coefficients on the initial relative weight of a staged rocket, if the value of the terminal velocity $V^{к}$ is to be maintained. A small change in the values of the structural coefficients s_i resulted in a reduction of the relative launching weight of the multistage rocket to 2/5 its former value. The question of the optimum characteristic coefficients has been specially considered by Yu. A. Pobedonostsev and K. P. Stanyukovich.*

Summarizing Table

Type	$\frac{V^{к}}{c}$	$\tilde{P}^{*}$	z_i			s_i			z^{e}
			3 st.	2 st.	1 st.	3 st.	2 st.	1 st.	
A, D	2.2	46	0.4	0.6	3.0	5.0	5.0	5.0	7.8
E	4.2	4100	3.0	3.0	3.0	5.0	5.0	5.0	63
B, C	4.2	1660	3.0	3.0	3.0	6.1	5.8	5.0	63
D-v	3.3	624	2.0	2.0	2.0	5.1	3.8	3.8	26
D-c	4.1	2740	3.3	2.7	2.7	5.7	4.7	4.7	58
Br	3.5	242	3.0	3.5	1.0	7.9	11.0	3.9	35
Van	3.9	910	2.1	3.2	2.8	7.0	7.7	4.4	50

Notes: Stages and subrockets are numbered from smaller to larger. A and D, B and C are Tsiolkovskii rockets; E is the "generalized" Tsiolkovskii rocket; D-v and D-c are Getland rockets; Br is Braun's rocket design; Van is the American "Vanguard" rockets.

A sample calculation of the optimum Tsiolkovskii numbers for the "Vanguard" rocket, carried out by these authors, led to a reduction of the relative launching weight to half its former value, while the ideal terminal velocity was maintained. B and C Tsiolkovskii rockets might seem to be the optimum version of the generalized E type, although special optimum calculations for these rockets have not been performed.

The figures for B and C rockets in the table show that for $c = 3000$ m/sec, $V^{i}_{к} = 12.6$ km/sec. Taking the velocity losses due to gravity and atmospheric resistance as 30%, the actual terminal velocity $V = V^{i}_{к} - \Delta V = 8800$ m/sec, in excess of circular velocity. If this loss is to be compensated for by a 30% increase in the velocity of the gas stream, $\Delta c = 900$ m/sec. For $c = 3900$ m/sec, therefore, B and C rockets attain an actual velocity exceeding escape velocity.

The computation of the optimum Tsiolkovskii numbers by the method of Pobedonostsev and Stanyukovich showed that the minimum relative weight of B and C rockets ($\tilde{P}^{0} = 1592$) is obtained for the following Tsiolkovskii numbers:

$$z_1 = 2.585; \qquad z_2 = 3.159; \qquad z_3 = 3.374.$$

As the summarizing table shows, the optimum values of the Tsiolkovskii numbers reduce the relative launching weight of a three-stage B or C Tsiolkovskii rocket by only 68 units. These rockets are therefore virtually the optimum version of rockets which have the structural coefficients indicated in the summarizing table (or in Table 3) and which attain a velocity $V_{к} = 4.2\,c$.

* Pobedonostsev, Yu. A. and K. P. Stanyukovich. "K raschetu optimal'nykh sootnoshenii stupenei sostavnoi rakety" (Calculation of the Optimum Relationship between the Stages of a Staged Rocket). — MVTU, Collection of articles, No. 88, 1958.

N66 37132

S. A. Shlykova

K. E. TSIOLKOVSKII'S CORRESPONDENCE WITH THE JET SCIENTIFIC RESEARCH INSTITUTE

(According to the Materials of the Archive of the Academy of Sciences of the USSR)

[Perepiska K. E. Tsiolkovskogo s RNNI (Po materialam arkhiva AN SSSR)]

The ideas of jet flight first began to be actualized in the Soviet Union at the end of the 1920's and beginning of the 1930's. The successes attained in the industrialization of the country at that period, and the development of scientific research on liquid-propellant jet engines created the prerequisites for a practical solution of the problem of building long-range rockets.

If Soviet rocketry scientists and engineers were known up to that time chiefly for their theoretical contributions, in the 1930's and 1940's they attained definite successes in the practical realization of jet flight. As early as the beginning of the thirties, the Soviet school of rocket engineering was taking shape. In 1931 jet propulsion study groups (GIRD) were formed in Moscow and Leningrad, and they played an important role in the development of Soviet rocketry.

The foundations of Soviet rocket engineering were laid by these groups, which included some of the most renowned Soviet rocketry experts, and by the Jet Scientific Research Institute (RNII), which was founded, with GIRD as its basis, in 1933.

In the very first weeks of its existence the leaders of RNII established contact with K. E. Tsiolkovskii, and it was maintained for the duration of his life. Some items from Tsiolkovskii's correspondence with RNII are given below.

Letter from the Head of the Jet Scientific Research Institute to K. E. Tsiolkovskii (RNII, 7 February, 1934, No. 82/s)

Dear Konstantin Eduardovich,

At the end of 1933, by a decision of the Government, the separate organizations and groups working on the problem of jet propulsion were amalgamated into the Jet Scientific Research Institute, which is responsible for the development and construction of aircraft whose motion is governed by the jet principle.

The dream of all researchers in this new field of human knowledge has thus been fulfilled: we have a base for tremendous development, from their scientific beginnings, of those ideas whose first herald you were.

There is no doubt that the organization of this Institute has been made possible only through the conditions created by the struggle of the many millions of the Soviet working classes, under the leadership of the Communist Party, for the Communist reconstruction of all of human society and for conquest of the heights of science and engineering.

We consider it indispensable to keep in close touch with you, the creator and contributor of the foundations of the theory of jet propulsion, and ask your consent to your appointment, in the near future, as one of the three or four leading workers of our Institute.

May we request a prompt reply by telegram.

With friendly greetings
I. Kleimenov*

Archive of the Academy of Sciences of the USSR, Folio 555, entry 3, file 108, sheet 1.

Tsiolkovskii answered this letter soon after receiving it. A penciled addition to the letter, in his hand, has been preserved: "Received 11 F[ebruary], 1934. Postcard and telegram (Come on 14 February '34) sent same day."

The organization of this Institute provided a scientific base for the further development and practical realization of the ideas on which Tsiolkovskii worked for many years.

As soon as four days after receiving this letter he outlined a work program for RNII, in which he included a whole series of problematic questions with which, in his opinion, the Institute should first of all be concerned.

RNII work program drawn up by Tsiolkovskii (15 February, 1934)

1. Choice of propellant and oxygen compound.
2. Choice of materials for (a) pumps, (b) ducts, (c) combustion chamber, (d) tapered duct, (e) tanks, (f) base.
3. Experimental testing.
4. Standing machine for explosion.
5. Determination of performance.
6. Consumption of the particles of the explosive mixture.
7. Automobiles.
8. Sledges,
9. Gliders.
10. Steering by rudder.
11. Lateral stability control vanes (bicycle).
12. Use of an elevator on two wheels (with a single axle).

* I.T. Kleimenov was at this time head of RNII and all of the Institute's correspondence with Tsiolkovskii, although it reflected the views of the entire RNII staff, was in his name.

13. Use of all control vanes on one wheel.
14. Application to gliders (rocket-propelled aircraft).
15. Flights and improvement.
16. Closed cabin flights higher than 5 kilometers.
17. As above, in a protective flying suit, without cabin.
18. Natural air purification of the cabin by means of plants. Choice of plants.

Archive of the Academy of Sciences of the USSR, Folio 555, entry 1, file 95.

Direct close contact was established between RNII and Tsiolkovskii, and on the day of the Red Army's sixteenth anniversary, a General Meeting of RNII workers made Tsiolkovskii an honorary member of the Institute's Engineering Board.

The resolution included the words: "To elect to honorary membership of the Engineering Board of RNII the first Soviet pioneer in the field of jet propulsion, Tovarishch Tsiolkovskii."

Archive of the Academy of Sciences of the USSR, Folio 555, entry 3, file 108, sheet 3.

When informed of this, Tsiolkovskii wrote as follows to the Head of the Institute: (9 March, 1934)

Dear Ivan Terent'evich,

I have just received your letter and am answering it the same day.

I hope by my work to show my gratitude to you and to all the workers of RNII.

I am sending your herewith an article on explosives.* Forward it to the journal, unless you feel it to merit secrecy, in which case I have no objection, as long as it is useful to the work than which nothing loftier has yet appeared on earth.

Regards to Tikhomirov and to the whole Institute.

K. Tsiolkovskii

Archive of the Academy of Sciences of the USSR, Folio 555, entry 3, file 108, sheet 4.

The Institute attributed great scientific value to Tsiolkovskii's article and regarded it as of great interest for workers in rocketry.

At this time the question of the periodic publication of RNII papers arose, and Tsiolkovskii was invited to be a regular contributor to these collections.** As a result the ties between RNII and Tsiolkovskii become even closer.

* The reference is to Tsiolkovskii's article "Energiya khimicheskogo soedineniya veshchestv i vybor sostavnykh chastei vzryva" (Energy of the Chemical Union of Substances and Choice of the Constituents of the Explosion), which appeared in Chapter VI of his manuscript work "Osnovy postroeniya gazovykh mashin i letatel'nykh priborov" (Fundamentals of the Construction of Gas Engines and Flying Machines) (Archive Acad. Sci. USSR, folio 555, entry 1, file 108).

** RNII papers came out in the form of collections with the title "Raketnaya tekhnika" (Rocketry). The first collection, published in 1936, was dedicated to Tsiolkovskii's memory.

Letter from the Head of RNII to K. E. Tsiolkovskii (27 May, 1935)

Dear Konstantin Eduardovich,

We have received from OVI RKKA your article "Energiya khimicheskogo soedineniya veshchestv i vybor sostavnykh chastei vzryva," and find it of great interest to workers in rocketry.

The collection "Trudy Reaktivnogo nauchno-issledovatel'skogo Instituta" (Papers of the Jet Scientific Research Institute) will be published in the near future, and we should like to include your article in it.*

If you consent, kindly inform us if you will authorize the editorial board to carry out a number of necessary changes in order to make the terminology and notation conform with those adopted by the Institute. Upon receipt of your reply we will send you the appropriate fee.

In the future "Trudy RNII" will appear periodically and we should greatly esteem having you as a regular contributor.

All here join me in thanking you for your greetings, and we send you in return our warmest regards.

In the next few days I shall be sending you our system of notation, and I should be very glad to have your opinion of it.

I. Kleimenov

Archive of the Academy of Sciences of the USSR, Folio 555, entry 3, file 108, sheet 9.

Notwithstanding his poor health, Tsiolkovskii quickly answered RNII, expressing his willingness to contribute regularly to the Institute's papers.

To I. T. Kleimenov, Head of RNII, from K. Tsiolkovskii (1 Tsiolkovskii St., Kaluga. 31 May, 1935)

Dear Ivan Terent'evich,

The editorial board has my authorization to edit my article "Energiya khimich[eskikh] soedinenii."

I willingly consent to this and will be most happy to be a regular contributor to the collection.

Thank you for your greetings and good wishes. Please forgive the brevity of this letter, due to the weakness of old age.

Regard to all.

Your Tsiolkovskii

Archive of the Academy of Sciences of the USSR, Folio 555, entry 3, file 108, sheet 11.

The Institute's scientists received Tsiolkovskii's agreement to participate in "Trudy RNII" with great satisfaction, since many of them became acquainted with the foundations of rocketry from his work, learned from him, and were infected by his enthusiasm and faith in the success of their work.

* The article was published in 1936, in the first issue of "Raketnaya tekhnika", pp. 42–49.

Letter from the Head of RNII to K. E. Tsiolkovskii (22-23 June, 1935)

Dear Konstantin Eduardovich,

All the scientists of our Institute heard of your consent to regular participation in "Trudy RNII" with great satisfaction.

As you know, many of those presently involved in practical work on rockets first became acquainted with the foundations of jet propulsion from your remarkable books, learned from them, and were infected by your enthusiasm and faith in the success of this work.

Your last article has already been sent to press, together with the other contents of the first collection, which will in all probability come out in August or September.

We are now beginning to prepare the second collection, in the hope of printing it early in September, and should like to see one of your new papers included in it.

The Engineering Board of the Institute has unanimously elected you to honorary membership and hopes that you will frequently participate in its work through consideration of reports which will be sent to you. Incidentally, we are sending you an article, chosen for the first collection, on the establishment of standard terminology for works on jet propulsion.* Your opinion of the questions touched upon in the article would be most valuable.

When this article was discussed by the Engineering Board of the Institute, a proposal was made, and accepted, to give your name to the ratio of the weight of propellant carried by the rocket to its remaining weight,** and to designate this quantity by the initial letter of your surname. We hope that this decision will have your approval.

Please accept our warmest good wishes.

I.Kleimenov
Head of RNII

Archive of the Academy of Sciences of the USSR, Folio 555, entry 3, file 108, sheets 14–15.

In his reply Tsiolkovskii made no objection to the proposed standardized terminology. Later he wrote, "It is necessary for all working in the field of jet propulsion, and I shall myself adhere to it from now on. My thanks to the members of the Institute for my election to the Engineering Board as honorary member. Greetings and congratulations to Langemak on the successful completion of his fine paper.

"I am very ailing, though I still spend the mornings working, on my feet, as before, with no days off. I have a lot to do. Now I am completing and copying "Trenie i soprotivlenie vozdukha" (Friction and Air Resistance),† a quite elementary, though mathematical paper. I can send it for consideration; perhaps it will be appropriate for the collection. My

* This was G.E. Langemak's article "O edinoi terminologii i sisteme oboznachenii v raketnoi tekhnike" (Standard Terminology and Notation in Rocketry), "Raketnaya tekhnika," I, pp. 9–17. 1936.

** Tsiolkovskii's number is now used to designate the ratio of the mass of propellant carried by the rocket to its remaining mass.

† The fourth chapter of Tsiolkovskii's manuscript work "Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov" (Archive Acad.Sci.USSR, Folio 555, entry 1, file 107).

deductions are very close to experimental results. In any case, when ready, I shall send you the essence of eleven chapters of my book ("Osnovy postroeniya gazovykh mashin. . . ". — S. Sh.). They are mutually independent, and you could choose any one of them for publication. First of all I shall send them. Regards to you and to the others at the Institute.

"The paper already sent to you on "Energiya khim[icheskikh] soed[inenii]" is one of the chapters of this book.

"Please do not talk to anyone, even me, about my illness.

K. E. Tsiolkovskii."

Archive of the Academy of Sciences of the USSR, Folio 555, entry 1, file 108, sheet 20.

Letter from the Head of RNII to K. E. Tsiolkovskii (7 July, 1935)

Dear Konstantin Eduardovich,

I read your letter with pleasure, and am happy to be writing to you again.

Please send us whatever you regard as already completed. All of the Institute's workers read your papers and impatiently await the new ones.

We are working indefatigably; a day or so ago several experimental rockets were launched to altitudes of the order of one or two kilometers to test some computations and designs. We are now carrying out a wide program of experimentation, both on test stands and on the proving ground, not, of course, as some craftsmen do, from the point of view of publicity, but from that of science, and our results are good. What a pity it is that you don't live in Moscow; I have been intending to visit you for three months, but unfortunately I fell sick with typhoid fever not long ago and have been unable to make the journey.

If you have no objection, I am thinking of coming to see you about the end of July or the beginning of August.

Best wishes from all at the Institute.

Yours, I. Kleimenov

Archive of the Academy of Sciences of the USSR, Folio 555, entry 1, file 108, sheet 16.

The technical correspondence between RNII and K. E. Tsiolkovskii continued until the end of the latter's life.

N66 37133

A. F. Tsander

*THE SCIENTIFIC AND ENGINEERING LEGACY OF F.A. TSANDER**
(O nauchno-tekhnicheskom nasledii F.A. Tsandera)

In his autobiography, written on 12 March, 1927,** Fridrikh Arturovich Tsander remarked: "In 1908 I made my first approach to work in the field of interplanetary travel. . .".

There exist manuscripts of Tsander, dating to 1908, 1909, and later years, in which he touched on questions of interplanetary flight. Beginning in the 1920's, and especially in 1924-1925, he talked a great deal about his work in lectures, which were plentifully illustrated with slides, originals, or photocopies now preserved in his private archive.

In 1924 Tsander's article "Perelety na drugie planety," part of a lecture which he had given on 20 January, 1924, to the Theoretical Section of the Moscow Society of Amateur Astronomers, was published in the Moscow magazine "Tekhnika i Zhizn'," No. 13. Due to his deep involvement in basic work in the aviation industry, however, he had no opportunity to spend much time preparing his papers for publication. In 1926 he appealed to Glavnauka for material assistance in the preparation for publication of a book of roughly 500 pages, presenting together with several of his papers an extensive table of contents; however, his request was refused.†

On 3 December, 1929, Fridrikh Arturovich sent his article "Polet daleko letayushchikh raket vne atmosfery" (The Flight of Long-Range Rockets Beyond the Atmosphere) to the editor of the magazine "Tekhnika Vozdushnogo Flota."†† In 1932 his article "Reaktivnye dvigateli i ikh kombinatsii s obyknovennymi dvigatelyami vnutrennogo sgoraniya" (Jet Engines and their Combination with Conventional Internal Combustion Engines) was printed in the first issue of the journal "Samolet."‡ In the same year Tsander's book "Problema poleta pri pomoshchi reaktivnykh apparatov," on which a lecture given by him in April, 1930, and chosen to be read at the Fifth International Hague Congress, was based, the article "Polet daleko letayushchikh raket vne atmosfery," and other writings of his were published. After this book Tsander planned to publish a book entitled "Raschet

* The article is based on a lecture given by the author in November, 1962, at the fourth Baltic Conference on the History of Science and Engineering.

** This autobiography was published by N.A. Rynin (N.A. Rynin. "Mezhplanetnye soobshcheniya" (Interplanetary Travel), fourth edition, pp. 190-193, Leningrad. 1929).

† The table of contents was published in 1961 (Tsander, F.A. "Problema poleta pri pomoshchi reaktivnykh apparatov. Mezhplanetnye polety" (The Problem of Flight by Jet propulsion. Interplanetary Flights), p. 444, Moskva, 1961). The original of the table of contents and the papers related to Tsander's appeal to Glavnauka are to be found in his private archive.

†† The Tsander archive contains the corresponding covering letter dated 3 December, 1929, together with other documents.

‡ This article, together with the covering letter, dated 26 September, 1931, is in the Tsander archive.

reaktivnykh dvigatelei i ikh kombinatsii s dvigatelyami drugikh vidov" (Designs for Jet Engines and Their Combination with Other Types of Engines). This is the first draft of a title which appears in a number of documents as "Raschet reaktivnykh dvigatelei i ikh kombinatsii s aviatsionnymi" (Designs for Jet Engines and Their Combination with Aero-engines). Tsander published it together with his contract with Aviaavtoizdat.* The manuscript of this book was left at GIRD when Tsander left for Kislovodsk.** The Tsander archive contains a two-page document headed "Materialy k knige 'Raschet reaktivnykh dvigatelei i ikh kombinatsii s aviatsionnymi" (Materials for the book "Designs for Jet Engines and Their Combinations with Aero-engines"), as well as the book's table of contents.† The first document shows that the materials for the book included designs of the ER-1 and ER-2 engines, the No. 7 nozzle (straight and inverted cone), etc.

After Tsander's death his scientific works remained almost wholly unpublished. In May, 1933, his widow handed a considerable part of his papers over to GIRD for publication. As is known, Tsander generally wrote his papers on space flight in shorthand, subsequently "deciphering" them and translating them into ordinary language. At present, according to the Academy of Sciences of the USSR, there exist 5267 pages of Tsander's work in shorthand, and 686 pages (with which the figure given by his widow when she transferred the papers to GIRD agrees) deciphered by Tsander himself. In the course of his protracted work in the aircraft industry Tsander produced a good many designs for ordinary aero-engines (according to the Academy of Sciences of the USSR Tsander left approximately 700 pages of papers on this subject in conventional writing; probably there are more in shorthand).

Soon after Tsander's death his shorthand system was discovered,†† making it possible to decipher all of the papers still in shorthand, and to publish whatever is of scientific or historical interest.

A number of works deciphered by Tsander himself were published posthumously, at first in the collections of "Raketnaya tekhnika" (1936-1937), then in the books "Problema poleta pri pomoshchi raketnykh apparatov" (1947), edited by M. K. Tikhonravov, and "Problema poleta pri pomoshchi reaktivnykh apparatov. Mezhplanetnye polety" (1961), edited by L. K. Korneev, which included previously published works of Tsander as well as some never before published. The last edition was extensively supplemented, largely by materials from the Tsander archive. Nonetheless, today a considerable part of Tsander's papers, including the designs of the ER-2 engine, GIRD-X rocket, etc., remain unpublished. The following

* Publication Contract No. 457 (Tsander archive).

** The Tsander archive contains a descriptive list, compiled by Tsander before his departure for Kislovodsk, of the things left in his desk at GIRD, in which this manuscript is included.

† Published in 1961 (Tsander, F. A. "Problema poleta..."(The Problem of Flight..)), p. 455, 1961.

†† It should be pointed out that shorthand is contained in the list of subjects taken by Tsander at the Technical High School in Danzig (the list is included in the official certificate given to Tsander and preserved in his private archive). At present, according to the description of the Academy of Sciences of the USSR, there exist 457 pages of translation from Tsander's shorthand notes into German, and 347 pages of translations from conventional German into Russian.

survey of Fridrikh Arturovich's work is based mainly upon his published works and what is known about them, and on the materials of his private archive. It must be taken into account, however, that only an insignificant part of Tsander's work is in the hands of his family. In particular, all those papers which, in accord with the standing rule, must have been left at GIRD after his death, are lacking in the private archive. Tsander's scientific writings still require special study and work, and the author of the present article does not claim to have given them an exhaustive treatment.

WORK ON METHODS OF ATTAINING ESCAPE VELOCITIES AND RETURNING TO THE EARTH

In his autobiography, written on 12 March, 1927, Tsander recalls that in September, 1917, he made "calculations relating to flights to other planets: [I] started with calculations of the flight of an especially high-flying airplane powered by a propeller engine; in the same year, for great velocities at high altitudes [I] added a rocket to the engine and performed calculations for it, as well."* It goes without saying that the idea of building a winged space craft might well have occurred to Tsander even before 1917. It would be of the greatest interest to study his early work on interplanetary flights.

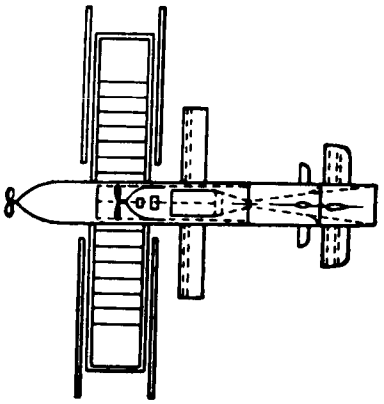

FIGURE 1. One of Tsander's space vehicle projects

The airplane-space vehicle is also recalled by the first Inventor's Questionnaire filled out by Tsander as early as 1921.**

In a manuscript dating to 1923,† Tsander wrote about his plan for an

* Rynin, N.V. "Mezhplanetnye soobshcheniya ...." (Interplanetary Travel...), Part 4, pp. 190-193.

** The questionnaire is preserved in GAORSS MO, Folio 2592, entry 1, file 19, No. 2.

† "Doklad inzh. F.A.Tsandera o svoem izobretenii: aeroplane dlya vyleta iz zemnoi atmosfery i pereleta na drugie planety" (Lecture of the engineer F.A.Tsander on his invention: an airplane for flight outside the earth's atmosphere and journeys to other planets). A fragmentary copy is preserved in the Tsander archive. The title is followed by a heading, "Read before the engineering committee of VSNKh...May, 1923," which has been crossed out; evidently the lecture was not held at the place mentioned. A complete summary of the lecture exists, and contains, at the end, expression of a wish to order an oil pump. This shows that Tsander subsequently decided to give this lecture at the "Motor" plant, where he was then working.

airplane-space vehicle: "My project was already considered to some extent, on 10 October, 1920, at about the period when I finished it, by a committee consisting of P. S. Dybenskii, P. A. Novikov, P. A. Moisheev, G. M. Mikhailov, Fedorov, and others. . . "

On 8 June, 1924, Tsander appealed for assistance to the Committee on Inventions, presenting to them an article "Opisanie mezhplanetnogo korablya sistemy F. A. Tsandera" (Description of F. A. Tsander's Space Vehicle), to which the appropriate patent formula was appended.* An illustration of the space craft discussed in this article is given in Figure 1.** It had to take off like an ordinary airplane, and in the lower layers of the atmosphere was propelled by a high-pressure two-cycle piston engine with oscillating cylinder, of Tsander's design. The engine ran on a liquid oxidant and liquid propellant (gasoline, petroleum, etc.), which had to be injected directly into the cylinder during the firing stroke. Up to an altitude of about 20 to 30 kilometers, the possibility of using the exhaust gases to create a jet thrust as a supplementary propulsive force was envisaged. Tsander's idea of replacing the carburetor by a pump which injected the fuel directly into the cylinder, which he developed in the course of designing this engine, was realized before World War II in a number of types of gasoline engines.

Further, beginning at an altitude of about 28 kilometers, by which, according to Tsander's calculations,a velocity of 350 to 450 m/sec would be reached, the space craft switched over to rocket-propelled flight, and the separate parts of the large airplane that had become superfluous began to be pulled inside the body and used to supplement the liquid propellant. At the termination of the boost phase a small rocket-propelled airplane, whose wings served for a glide landing (the engine, as described above, was available for a possible combined landing), was left. Tsander pointed out that the thrust of the rocket he had designed equalled only 1/6 to 1/3 the weight of the whole craft, and that adoption of a glide landing permitted a weight reduction to one-fifteenth or one-twentieth that of a craft using a rocket engine to land.

The twelfth number of the Moscow journal "Tekhnika i Zhizn' " (1924) had on its cover a drawing of Tsander's space craft. Besides this, it was reported in an article by the astronomer A. A. Mikhailov that "recently a new plan for a space travel craft, based on Tsander's ideas, had been developed here, and an article dealing with it will be included in one of the forthcoming numbers of the journal."† The article by Tsander referred to

* The article was published only after Tsander's death, but without the patent formula, which is not found in all of the copies ("Raketnaya tekhnika," No. 5, 1937). A number of copies are to be found in the private Tsander archive, together with the reply Tsander received from the Committee on Inventions (they refused his request, on the grounds that his proposals were on the whole impracticable).

** The little rocket-propelled airplane is not fully illustrated in the sketch which Tsander presented to the Committee on Inventions. In the text of the article "Opisanie mezhplanetnogo korablya sistemy F. A. Tsandera," however, it is recalled that the small airplane is enclosed within the body of a large one, and that at the end of the boost phase, the little airplane is left with a shortened body. It therefore seems possible to insert here the sketch, from the Tsander family archive, of a space craft, in which the structural scheme is most fully illustrated.

† Mikhailov, A.A. "Mezhplanetnye puteshestviya" (Interplanetary Travel), "Tekhnika i zhizn', No. 12, p. 12, 1924. Mikhailov was head of the Moscow Society of Amateur Astronomers, to the Theoretical Section of which Tsander lectured about his work, on 20 January, 1924.

here was published, with the title "Perelety na drugie planety," in the following number (13).* In this article certain proposals were published for the first time in the world's literature; to built a winged space craft to facilitate flight in the atmosphere; to use the structural material of the craft (in particular, metals) as one of the fuel components; to descend from outer space on to planets possessing an atmosphere by gliding flight, using the atmosphere as a braking medium and avoiding wastage of propellant; to use the pressure of light for flight in outer space, etc. As a possible variation, the use of a jet engine, instead of a piston engine of the type described above, for flight in the lower layers of the atmosphere, was also considered in the article.** Tsander remarked that he had been making calculations relating to the design of space vehicles for a number of years, and wrote: "The calculations carried out clearly indicate the full possibility of a slow safe glide landing on the earth." The article contained some results results of computations and a schematic diagram of the airplane-space vehicle which he presented to the Committee on Inventions.

Many ideas expressed by Tsander in the articles "Perelety na drugie planety" and "Opisanie mezhplanetnogo korablya sistemy F. A. Tsandera," as well as earlier in his lectures, and first theoretically worked out by him, are widely discussed in the literature of the present day. Among them are, in particular, the ideas of building a winged space vehicle, of using a jet engine to power flights in the lower layers of the atmosphere, or of glide landings.† For example, in America it is proposed to build for orbital flight and return to the earth a space craft powered by a jet engine in the lower atmospheric layers, and from a height of 30 kilometers, by a rocket engine intended to run on liquid hydrogen and liquid oxygen.†† It was calculated that the cost of putting into orbit one kilogram of payload would be six times lower, using this type of aircraft, than with a regular carrier rocket such as is used at the present day.‡ Tsander also envisaged the use of liquid oxygen and liquid hydrogen in a rocket engine, beginning at a height of approximately 30 kilometers (the limits mentioned by Tsander are 28 to 35 km).‡‡

* Tsander produced two versions of this article, both written in 1923, as is evident from his manuscript "Stat' i v oblasti mezhduplanetnykh soobshchenii, napisannye mnoyu" (Articles Written by Me in the Field of Interplanetary Travel). The later (abridged) version was printed in 1924, and the earlier, only after Tsander's death (Tsander, F.A. "Problema poleta...," p.222). He read one of the versions of the article as a lecture to the Theoretical Section of the Moscow Society of Amateur Astronomers on 20 January, 1924.

** Some of the suggestions contained in this article were also published by others, but subsequently (for example, Hohman, W. "Die Erreichbarkeit der Himmelskörper," München, 1925; Tsiolkovskii, K.E. "Issledovanie mirovykh prostranstv reaktivnymi priborami," Kaluga, 1926). Tsiolkovskii's article "Kosmicheskii korabl'," of 24 June, 1924, written at the request of the Izdatel'stvo Transpechati was also published in the magazine "Tekhnika i zhizn'," after Tsander's article. Besides this, it should be taken into account that even before they appeared in print, Tsander expressed his ideas in lectures and in his application to the Committee on Inventions. He was therefore the first to make the proposals mentioned.

† See, for example, "Aviatsiya i kosmonavtika," No. 1, p. 21. 1962.

†† Express information of the Academy of Sciences of the USSR, No. 6 (36), No. 13 (74). 1963.

‡ Express information of the Academy of Sciences of the USSR, No. 6 (36), 1963.

‡‡ See, in the next section of this article, the places where the article "Raschet rakety mezhplanetnogo korablya" (Design of a Space Vehicle Rocket), is discussed, as well as the book: Tsander, F.A. "Problema poleta...," pp. 24-29, 52-55, 1932, and Tsander's article "Perelety na drugie planety" (for example, in the book: Tsander, F.A. "Problema poleta...," pp. 267-279. 1961).

A very urgent problem connected with space craft design is that of the high temperatures which must occur during landing due to the thermal effect of the air flow on a space vehicle moving through the atmosphere with high velocity. Tsander devoted the article "O temperature, kotoruyu primet mezhplanetnyi korabl' pri planiruyushchem spuske na Zemlyu" (The Temperature Acquired by a Space Vehicle Making a Glide Landing upon the Earth) to this question. B. P. Plotnikov, who edited this article before its publication in 1961, remarked that "several of the values given in the paper for the temperatures of the body and weight of the thermal shield of the craft making a glide landing are close to the values of these quantities given by contemporary methods of heat exchange calculation." In his article Tsander presents two methods for thermal protection of the space vehicle from aerodynamic heating.

Together with his calculations for gliding descent Tsander also devoted himself to theoretical study of ballistic descent in the article "Planiruyushchii spusk s mezhplanetnogo prostranstva do poverkhnosti Zemli" (Gliding Descent from Outer Space to the Surface of the Earth), which he presented to Glavnauka in 1926 (it was first deciphered in 1924, as is evident from the manuscript preserved in the Tsander archive).

Tsander's article "Raschet poleta mezhplanetnogo korablya v atmosfere (pod'em)" (Flight Calculations for a Space Vehicle in the Atmosphere (Ascent)) was devoted to theoretical study of the ascent of a space craft into outer space. In the paper "Sravnenie raskhoda topliva dlya sluchaya, kogda kislorod beretsya iz atmosfery, i dlya sluchaya, kogda on zapasen v rakete" (A Comparison of Fuel Consumption in the Cases when the Oxygen is Obtained from the Atmosphere and when it is Stored in the Rocket), Fridrikh Arturovich developed the theory of space craft boost in the atmosphere, using atmospheric air, and in particular, incorporating jet engines.*

Tsander observed that the space vehicles he proposed "can be used, aside from space travel, for urgent rapid flights on the earth, in the highest layers of the atmosphere and above it; they can transport freight and passengers from one place on the globe to another, as well as to interplanetary stations, and from them back to the celestial bodies which they orbit."** Specifically, Tsander envisaged the development of jet aviation. He considered the constant improvement of aviation through the gradual attainment of ever higher velocities and more distant and higher-altitude flight as the path to the realization of his ideas on the construction of space craft. In line with this idea, for example, he nurtured the thought of first installing a small model engine of the above-mentioned type in a light

* Information in the Tsander archive shows that these papers had been deciphered by the middle of the 1920's.

** "Opisanie mezhplanetnogo korablya sistemy F. A. Tsander, inzhenera-tekhnologa" (Description of a Space Vehicle of F. A. Tsander's Design), Tsander archive. First published in the collection "Raketnaya tekhnika," No. 5, 1937.

aircraft,* and he attributed great importance to experimental aerodynamic studies of airfoil profiles and rocket models (Tsander's private archive contains a sheet with a drawing and an inscription by him: "Summary of Lecture Proposed for First All-Union Experimental Aerodynamics Conference, on the theme, "Ispytanie profilei kryl'ev i modelei raket dlya tselei sverkhavaitsii" (Testing of Airfoil Profiles and Rocket Models for the Purposes of Super-Aviation)).

Tsander did not limit his search for the best space vehicle designs to a single direction. He thought that each method should be confirmed by experiments depending upon the objectives of the flight, the general development of engineering, etc. This was particularly reflected in the practical work program which he proposed in his organizational address to the Scientific Research Section of the Society for the Study of Interplanetary Travel, on 15 July, 1924. He suggested testing various designs, including "complex rockets, inserted one into another," i.e., in current terminology, multistage rockets.**

In 1928 Tsander had the idea of a special kind of staged rocket, consisting of a large central rocket surrounded by a number of lateral rockets, together with vessels for propellant and hydrogen; both the vessels and the lateral rockets, according to Tsander, would serve, after being used, as fuel for the central rocket.† This plan appeared in print in 1932.†† Tsander observed that it would be possible to construct a rocket of this type, in which "the terminal weight would equal only 1/1000 of the initial weight, i.e., one part would receive energy from 999 combustible parts; such great fuel consumption is not required, even for flight to another planet." As is evident from the program in the book "Raschet reaktivnykh dvigatelei i ikh kombinatsii s dvigatelyami drugikh vidov," Tsander had calculated the "resistances to flight" of such a staged rocket.‡ In the book "Perelety na drugie planety, pervyi shag v neob'yatnoe mirovoe prostranstvo," whose table of contents Fridrikh Arturovich presented to Glavnauka in 1927, he

* Tsander expressed this idea, for example, in the following sources: "Doklad inzh. F.A. Tsandera o svoem neftyano-kislorodnom dvigatele..." (Tsander's Lecture on His Petroleum and Oxygen Engine); "Doklad inzh. F.A. Tsandera na zasedanii byuro yacheiki RKP Gos-Avia-Zavoda No.4 imeni t. Frunze (b. "Motor") ot 27 aprelya 1925 g. (these words were crossed out by Tsander) o rabotakh, predlagaemykh im dlya vypolneniya ot imeni yacheiki ODVF na oznachennom zavode v oblasti aviatsii i vysoko letayushchikh raket s tsel'yu: pomoshchi kul'turnomu i voennomu delu i podgotovki k mezhplanetnym puteshestviyam" (Lecture of F.A. Tsander at a meeting of the Communist Party cell of the Government Aircraft Plant No.4 imeni Comrade Frunze (formerly "Motor"), on 27 April 1925 (these words were crossed out by Tsander), on the work which he proposes for completion at the aforesaid factory, on behalf of a cell of the Society of Friends of the Air Force (OVDF), in the realm of aviation and high-altitude rockets; with the goal of furthering cultural and military causes and preparing for space travel)—Tsander archive.

** Tsander, F.A. "Problema poleta...." (The Problem of Flight....), p.444, par.9. 1961. The original program is in the Tsander family archive.

† Tsander made drawing of a staged rocket of this type as early as June, 1928, as is evident from the notebook preserved in the private archive. M.K. Tikhonravov assumes that Tsander touched upon the question of this rocket in his address to the Commission on Scientific Aeronautics at the Moscow Aerological Observatory in November, 1928 (Tsander, F.A. "Problema poleta...," p.17 and p.213, footnote 2, 1947). The Tsander archive contains a corresponding notice announcing the forthcoming meeting of the Commission on 30 November, 1928, and mentioning the address in question with the title "Predvaritel'nye raboty po postroike reaktivnogo apparata" (Preliminary Work for the Construction of a Jet Craft).

†† Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p.51, 1932.

‡ See footnotes ** and † on p. 134.

planned to dedicate one of the chapters to the design of "rockets consisting of two or more rockets, one inside another, on the lines of Oberth's idea."*

LIQUID-PROPELLANT ROCKET ENGINES AND ROCKETS

The manuscript of Tsander's article "Raschet rakety mezhplanetnogo korablya" (Design of a Space Vehicle Rocket), on which the dates of deciphering - 13, 16, and 17 January, 1924 - have been noted, has been preserved in the Tsander archive. The article gives calculations of the thrust of a liquid-propellant rocket engine, efficiency coefficients, and a method for the thermal calculation of such an engine from ideal gas formulas, using entropy diagrams and taking into account heat transfer to the walls and friction. The concluding part of the manuscript is titled "numerical example," and refers to the calculation of a hydrogen and oxygen rocket with a thrust of 1.5 tons, using entropy diagrams. The manuscript is not complete: a special paragraph devoted to a calculation of "the heat passing through the walls" is missing, although there are references to this calculation, and the numerical example is not completed.**

It should be remarked that the summary of Tsander's address to the Theoretical Section of the Moscow Society of Amateur Astronomers on 20 January, 1924, contains a section with the same title as this article,† and with paragraphs devoted to the incomplete calculations in the manuscript article; for example, "Raschet teploty, otvodimoi cherez stenki i tolshchiny stenok" (Calculation of the Heat Drawn off Through the Walls and of the Thickness of the Walls). Probably the paper was deciphered in connection with its preparation as a lecture.

Furthermore, Tsander presented this article to Glavnauka in 1926. Professor V.P. Vetchinkin, the reviewer, to whom Tsander's text was submitted, observed, in his opinion of 8 February, 1927, that Tsander "...was concerned with the constructive resolution of fundamental questions of rocket design, such as the analysis of the nozzle and its cooling, which is evidently the greatest obstacle to the realization of rocket-propelled flight."††

Tsander published some of the results of his research on a hydrogen and

* Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p.447, par.14, 1961.

** There also exists a partially edited typewritten text of the article, but the numerical example is missing there, too, and the heading has been changed, so that the article has a new title: "Teplovoi raschet raket" (The Thermal Calculation of Rockets).

† Tsander, F.A. "Problema poleta...", (The Problem of Flight...), p.442, 1961. The original of the summary is located in the Tsander archive. When it was printed as part of a book the date of Tsander's address was filled in, since at that time it was missing in the original. However, comparison of the heading of the "Konspekt" (Summary) ("Konspekt lektsii o moem mezhplanetnom korable, chitannoi v teoreticheskoi sektsii Moskovskogo obshchestva lyubitelei astronomii" (Summary of Lecture on My Space Craft, Read to the Theoretical Section of the Moscow Society of Amateur Astronomers)), and its contents with the heading and contents of "Rezyume doklada F.A. Tsander o konstruktsii ego mezhplanetnogo korablya i o pereletakh na drugie planety, chitannom v teoreticheskoi sektsii Moskovskogo obshchestva lyubitelei astronomii 20 yanvarya 1924 goda" (Resume of F.A. Tsander's Lecture on the Design of his Space Craft and on Flights to Other Planets, Read to the Theoretical Section of the Moscow Society of Amateur Astronomers on 20 January, 1924) (see Tsander, F.A., "Problema poleta...," p.27. 1961; the original is in the Tsander archive) shows that the "Konspekt" was actually written for the lecture.

†† Tsander, F.A. "Problema poleta..." (The Problem of Flight...), pp.37-40. 1961.

oxygen rocket with a thrust of 1.5 tons in the book "Problema poleta pri pomoshchi reaktivnykh apparatov," which appeared in 1932. The article mentioned above was printed only after Tsander's death, with the title "Teplovoi raschet raketnogo dvigatelya na zhidkom toplive (stat'ya vtoraya)" (Thermal Calculation for a Liquid Propellant Rocket Engine (Second Article)),* partly in abridged, and partly in expanded form (the paragraph "Rezul'taty rascheta teploty, prokhodyashchei cherez stenki kamery sgoraniya" (Results of the Calculation of the Heat Passing Through the Walls of the Combustion Chamber) was added). In the last paragraph results of calculations of the temperature of the walls of the combustion chamber in the presence of a swift-flowing cooling liquid (water) were adduced. Through them Tsander came to the conclusion that it was possible to construct an all-metal engine without using fireproof coatings, although this had not yet been proved experimentally at that time, and was only verified later.

In his other article on the same subject, Tsander presented an approximate calculation of the combustion temperature of the components of the propellant mixture, taking dissociation into account, gave a method for the approximate determination of the dimensions of the necessary combustion space, presented an approximate calculation of the temperature of the combustion chamber walls, assuming cooling of the walls by a moving liquid or gas (as an example Tsander took an oxidant, liquid air enriched with oxygen), etc. This article also did not appear in print until after Tsander's death.**

Nowadays equilibrium constants are widely used in determining composition and temperatures of combustion products in liquid-propellant rocket engines. Although references to these quantities are lacking in Tsander's published works, his private archive contains a number of papers in which equilibrium constants figure.

In particular, there are the first two pages of a manuscript "K raschetu vodorodno-kislorodnykh raket" (Aids to the Calculation of Hydrogen and Oxygen Rockets) (Figure 2), dated 15 March, 1926. There is also a "Tablitsa teplosoderzhaniya i, entropii s, vydelennoi teploty Q i postoyannoi ravnovesiya $-lg\ K$ dlya vodyanogo para po Piru v ikh zavisimosti ot temperatury t i τ" (Table of Enthalpy i, Entropy s, Heat Liberated Q, and equilibrium constant $-lg\ K$ for Steam, According to Pir, as Functions of the Temperature t and τ), and still another table, related to the thermal calculation of liquid-propellant rocket engines, together with the preceding one on a double sheet.† The sheets containing these tables are numbered 16–18 (the columns on page 17 are not filled in, which shows that the two tables contain only a part of Tsander's thermal calculations for liquid fuel rocket engines). He covered two pages of a leaflet entitled "Tablitsy postoyannykh velichin, vazhnykh dlya rascheta reaktivnykh dvigatelei" (Tables of Important Constants for Jet Engine Calculations) with a series of dissociation reactions ($H_2 \rightleftarrows 2H$; $2H_2O \rightleftarrows 2H_2 + O_2$; $2CO_2 \rightleftarrows 2CO + O_2$; $H_2 + CO_2 \rightleftarrows CO + H_2O$; $N_2 + 2H_2O \rightleftarrows 2NO + 2H_2$; $H_2 + O_2 \rightleftarrows H_2O_2$). In the case of the first

* "Raketnaya tekhnika," No. 5, pp. 77-90, Moskva-Leningrad. 1937.

** "Teplovoi raschet raketnogo dvigatelya na zhidkom toplive" (Thermal Calculations for a Liquid-Propellant Rocket Engine), "Raketnaya tekhnika," No. 1, pp. 97-120, Moskva-Leningrad. 1936.

† The specific heats C_v and C_p, for example, are included in the second table, but it has not proved possible fully to decipher its heading. In the first table, the column headed $\lg K$ is blank, and the column headed Q contains only one entry. Tsander evidently intended to fill them in later.

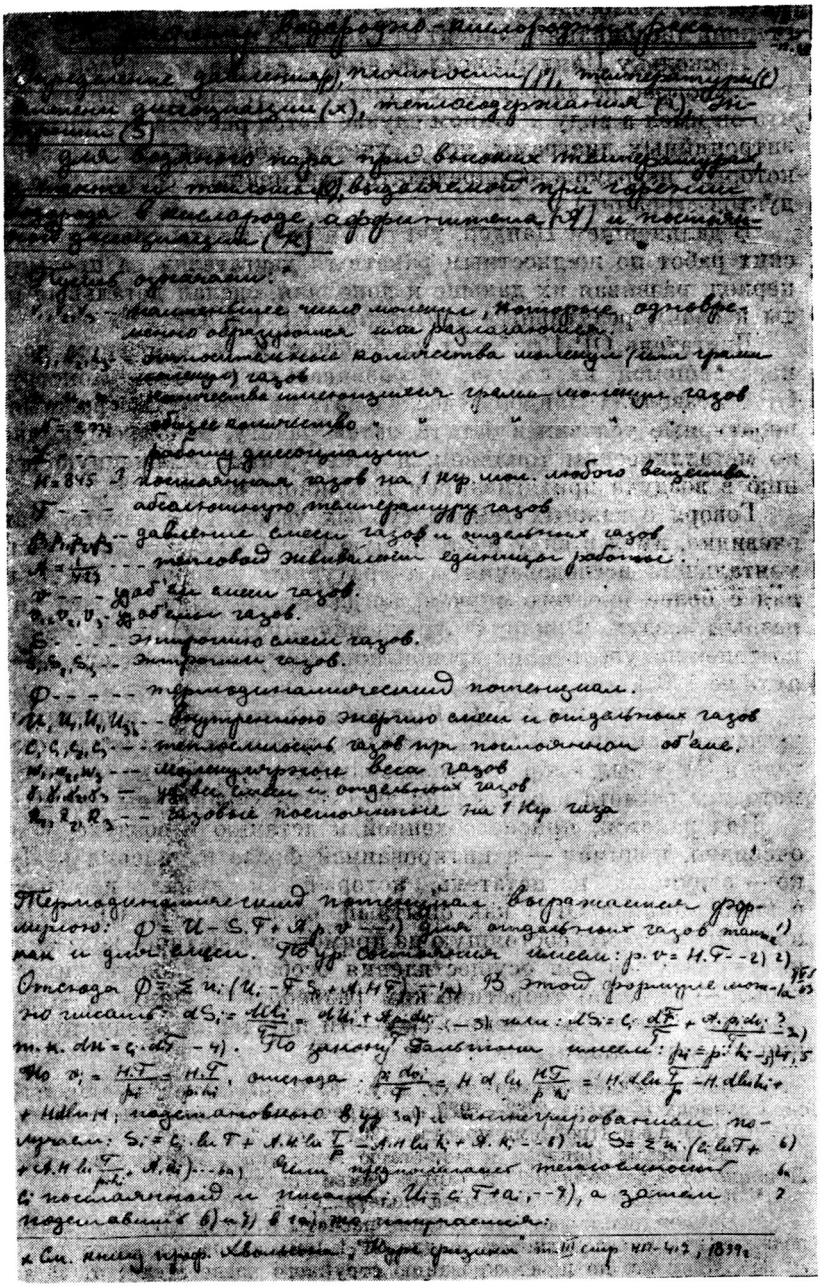

FIGURE 2. First page of Tsander's manuscript

"K raschetu vodorodno-kislorodnykh raket" (15 March, 1926)

four reactions, the most recent chemical advances enabled him to express the logarithms of the equilibrium constants K_c as functions of the absolute temperature; for the last two reactions he gives only references to relevant literature. He also wrote down the ratio of the equilibrium constants K_c and K_p and found an expression in K_p of the dependence of the reaction $H_2 \rightleftarrows 2H$ on the stage of dissociation and the general pressure. Finally, he began an approximate computation of the Nernst Chemical equilibrium.* These dissociation reactions and their equilibrium constants were calculated for a liquid-fuel rocket engine running on liquid air and a hydrocarbon.**

Tsander submitted to Glavnauka, as his own statement to them, of 3 October, 1926, shows, his abridged translation from German of Professor Tsentnershver's article "K teorii dissotsiatsii gazov" (A Contribution to the Theory of Gas Dissociation), which considers the reaction $2H_2 + O_2 \rightleftarrows 2H_2O$ with particular reference to its equilibrium constants, which are given. The translation is in the Tsander archive.

Equilibrium constants also enter into the entropy diagram calculation of liquid-fuel rocket engines. The last paragraph of Tsander's article "Teplovoi raschet raketnogo dvigatelya na zhidkom toplive (stat'ya vtoraya)" has, on this subject, a footnote reference to Schule's book "Tekhnicheskaya termodinamika" (Engineering Thermodynamics). There is another reference to this work in one of the papers related to Tsander's lectures at the Moscow Aviation Institute in 1930–1931.† Schule applied equilibrium constants to the compilation of entropy diagrams, but not, as Tsander did, to liquid-fuel rocket engines.

If these papers of Tsander, and the fact that his output grew with time, are taken into account, it must be concluded that there are more detailed papers (either his own, or produced under his supervision and in accord with his methods) dealing with equilibrium constants. In the first article entitled "Teplovoi raschet raketnogo dvigatelya na zhidkom toplive," the section headed "Opredelenie temperatury sgoraniya s uchetom dissotsiatsii gazov" (Determination of Combustion Temperature Taking Gas Dissociation into Account) contains the remark: "To be quite precise, it must be observed that composition of the combustion products is not the same in the presence of dissociation, as when it does not occur. For simplification it can be assumed that there is small change in enthalpy. Furthermore, the degree of dissociation depends upon the pressure in the chamber..."

Since Tsander mentioned this subject without touching on entropy diagrams, it is readily deduced that he had in mind a calculation method that did not employ entropy diagrams, but took into account equilibrium

* The leaflet is undated, but the cited literature covers the years 1893 to 1923. Tsander wrote that "the formulas are without exception taken from the newest sources which take into account the oldest material, and the reference tables are in part abridged, with some computations performed by the copyist." "K raschetu vodorodno-kislorodnykh raket" and "Tablitsy postoyannykh velichin..." occupy two full pages and are both broken off in the middle of a sentence, which suggests that somewhere their continuation can be found.

** Two things make this evident: first, Tsander wrote two formulas involving nitrogen; second, he performed calculations for this engine again (e.g., in the article published as "Teplovoi raschet raketnogo dvigatelya na zhidkom toplive (stat'ya pervaya)"). Other evidence is adduced below.

† A document in the Tsander archive has the headings: Moscow Aviation Institute. Engineering Society. Fundamentals of Jet Propulsion. Jet Engines. Task No. 1. Work Program. Literature.

constants, without which the variable composition of the combustion products of a gas cannot be determined.

When, later on, Tsander evaluated and extended his previous theoretical research on liquid-propellant rocket engines, he made detailed calculations for the ER-1 and ER-2 jet engines of his own design.*

The ER-1 engine, running on gasoline and gaseous air, fed from a vessel, developed a thrust of 5 kg. The design of the ER-1 permitted Tsander to "study the most important thermal conditions in a rocket, and subsequently, rockets running on partly metallic fuel and rockets adapted for aerial flight using attraction of the external air."**

Tsander evidently was thinking of the evolution of a method for the experimental study of thermal conditions in liquid-propellant rocket engines, starting with the most simple case, when gaseous air serves as an oxidant. He envisaged gradual increase of the oxygen content to 100%.

E. S. Shchetnikov, who prepared part of Tsander's calculations on the ER-1 for publication, pointed out that despite the choice of atmospheric air as oxidant, the design and trial of the engine and the method of computation, are characteristic of liquid-propellant rocket engines.†

In speaking of a rocket adapted for aerial flight Tsander evidently was referring to a jet supercharger, which he planned to use in conjunction with the ER-1 as an experimental model.†† He constructed a system, consisting of straight and inverted cones, designed to create a special thermal cycle, which, according to his theoretical results, would give the combustion products a greater exhaust velocity.‡

Tsander set about designing the ER-1 in 1928,‡‡ and he probably referred to it in his lecture "Predvaritel'nye raboty po postroike reaktivnogo apparata" (Preliminary Work for the Construction of a Jet Craft), delivered before the Committee on Scientific Aeronautics on 30 November, 1928.

The ER-1 was the first experimental Soviet jet engine to be built on rigorous scientific principles. Tsander's computations relating to it occupied more than 145 pages, as can be seen in his manuscript "Materialy k knige 'Raschet reaktivnykh dvigatelei i ikh kombinatsii s aviatsionnymi'." He tested the ER-1 more than 50 times. It served as a basis for the ER-2, in making computations for which Tsander on the whole anticipated GIRD.

One of the similarities between the ER-2 and its predecessor was that the oxidant, which entered the combustion chamber in gasified form, left the exhaust as a liquid.

* As E.S. Shchetnikov points out, computation formulas for the ER-1 are encountered in Tsander's shorthand notes for 1922-1929. (Tsander, F.A. "Problema poleta...,"(The Problem of Flight...), p. 206. 1961.

** From Tsander's letter of 4 December, 1929, to E.V. Lutsenko, Secretary of the Aviasektsii Zakosoaviakhima (Tsander archive).

† Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p. 206.

†† Tsander performed the corresponding computations and ordered the design of a jet supercharger for the ER-1 (see AN SSSR, opis' No. 254, "Zadanie po proektirovaniyu struinogo nagnetatelya," (Order for Design of Jet Supercharger), 18 January, 1931 (No. 185)).

‡ On the theory of thermal cycles see Tsander, F.A. "Problema poleta..." (The Problem of Flight...), pp. 16-23, 1932. An illustration of the system of straight and inverted cones constructed by Tsander for the ER-1 is found on p. 47 of "Problema poleta...", Moskva, 1961.

‡‡ The Tsander archive contains a sketch of a blowtorch, dated 23-24 July, 1928 (when designing the ER-1, through shortage of materials, Tsander had to use some of the parts of a blowtorch), and sketches, dated 26-30 July, 1928, 31 July, and 2 August, 1928, of parts of the ER-1. There is also a sketch of the ER-1, dated 22 and 24 April, 1929. In addition, one of the shorthand notes in the archive contains drawings, dating from July, 1928, connected with the design of the ER-1.

In his lectures at the Moscow Aviation Institute in 1930–1931, Tsander discussed his "own flying rocket design," and devoted considerable attention to liquid-propellant rocket engines running on liquid air and gasoline. He gave his students the assignment of determining the combustion temperature of a rocket running on alcohol and oxygen, having first demonstrated the method in the case of a petroleum and oxygen rocket.*

In April, 1932, having already amassed a great deal of scientific knowledge and engineering know-how, Tsander began to work for GIRD, which built and tested the ER–2 engine and launched the GIRD–X rocket, the first in the Soviet Union to have a liquid-propellant engine. For one version of the GIRD–X Tsander designed a film cooling system, such as was widely used several years later in the German FAU–2 rocket.

Tsander designed other liquid-propellant rocket engines with thrusts of 600 kg and 5 tons. One of the variations of the latter was intended to incorporate a gas turbine to operate centrifugal fuel pumps, a system which later found wide application.

Tsander's work on rockets did much to further Soviet rocket engineering. The monument to him, erected in Kislovodsk in 1959, bears the inscription, "Fridrikh Arturovich Tsander, pioneer of Soviet rocket engineering," and mounted on it is a model of the GIRD–X rocket.

METALLIC FUELS

As early as 11 March, 1909, Tsander, thinking about the problem of building a rocket capable of escaping from the atmosphere, made a note in one of his manuscripts about "the desirability of using the entire mass of the rocket as fuel."** On the basis of the following premises, Tsander regarded as one of the advantages of this idea the fact that it would permit construction of a less cumbersome space craft.

1. If parts which become superfluous after some stage in flight can be used as fuel, it is possible to build a space craft with quite a large relative fuel mass $M_т/M_0$, where $M_т$ is the initial fuel mass, and M_0, the initial mass of the craft.

2. Since several highly calorific metals constitute efficient fuel, their combustion should result in increased relative exhaust velocity of the combustion products.

In the article "Perelety na drugie planety" Tsander wrote: "During flight. . . molten metal must be ejected to increase the performance of the rocket."† The same idea was expressed more clearly in "Opisanie mezhplanetnogo korablya sistemy F. A. Tsandera": "The liquid metal is then sprayed in, partially evaporates and mixes with the oxygen burning in the chamber. The combustion of a highly calorific metal increases the temperature of the gaseous products and therefore the efficiency of the rocket."††

* "Programma po reaktivnym dvigatelyam i mezhplanetnym soobshcheniyam v raketnoi sektsii ANTO MAI 1931." (Jet Engine and Space Travel Program of the Rocket Section of ANTO MAI, 1931), Tsander archive. See also footnote † on p. 143.

** Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p. 71. 1932.

† See Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p. 268. 1961.

†† Ibid., pp. 281-282.

In "Perelety na drugie planety" Tsander adduced some figures for a space craft in which the structure is partially used as fuel. He wrote: "This creates a practical possibility of reducing the craft's full weight of 10,000 kg to 500 kg (the weight of small land-based airplanes) by the consumption of combustible material, and fully guarantees attainment of the enormous velocities required to overcome gravity."

Even fuller evidence of Tsander's calculations on this subject is found in the outline of a lecture which he planned to give in May, 1923.* He pointed out that if all parts of the space craft which had become superfluous at a certain altitude were used as fuel, "in the case of liquid oxygen, hydrogen, and Duralumin, a reduction to one twentieth of the initial weight would result in a terminal velocity of 11.3 km/sec. If gasoline were used instead of hydrogen, the terminal velocity, assuming the same reduction in weight, would be 7... km/sec,** enough to orbit the earth like the moon.

There is also evidence that at his lecture to the Theoretical Section of the Moscow Society of Amateur Astronomers, in January, 1924, Tsander showed tables of "calorific power of several metals, with the exhaust velocities resulting from their use."†

In general, Tsander devoted a good deal of attention to the problem of propellants, and in particular suggested using plastics as fuel,†† with fluorine as oxidant.‡ The basic difficulty in using metallic fuels was the occurrence of nonvolatile combustion products (metallic oxides). Fridrikh Arturovich devoted theoretical study to the question, and in the article "Reaktivnye dvigateli, rabotayushchie materialami, dayushchimi ne tol'ko letuchie, no i tverdye produkty goreniya" (Jet Engines Running on Fuels Giving Both Volatile and Solid Combustion Products)‡‡ he gave an approximate determination of the thrust of such an engine, the difference in velocities of the volatile and solid combustion products leaving the nozzle, and the drop in temperature of the oxygen particles while in the nozzle. Interestingly enough, the table of contents of the book presented to Glavnauka in 1927 contains, together with the chapter headings devoted only to the subjects mentioned above, a heading concerned with more extensive calculations, and specifically, with exact calculations of such an engine, including differential equations for determination of the density, temperature, pressure, and velocity of the gases, temperature and velocity of the solid particles, temperature of the walls and coolant for various nozzle cross sections, and of solutions of this system of equations. The same chapter also included a discussion of the approximate and exact determination of the time during which the gases and solid combustion products remained in the engine, and of the composition of the combustion products for a given ratio of metal to fuel. Tsander's research on this last question was printed only after his death in the article "Voprosy konstruirovaniya rakety,

* On this lecture, see the footnote † on p. 135.

** In the manuscript the number is illegible.

† "Rezyume doklada F.A. Tsandera..." (Resume of F.A. Tsander's lecture...), (Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p. 27. 1961.)

†† Tsander, F.A. "Problema poleta..." (Problem of Flight...), p. 43. 1932.

‡ Ibid., p. 45.

‡‡ It was published posthumously with the title "Primenenie metallicheskogo topliva v raketnykh dvigatelyakh" (Use of Metallic Fuel in Rocket Engines), "Raketnaya tekhnika," No. 1, pp. 121-135, Moskva-Leningrad. 1936.

ispol'zuyushchei metallicheskoe toplivo" (Questions in the Design of Metallic Fuel Rockets), composed of abridgements of several of Tsander's papers.* The article also discussed the requirements imposed upon the metals or alloys used as fuel, and reflected the results of experiments on the combustion of metals, carried out under Tsander's direction in 1928.

These experiments subjected various means of using metals or metallic alloys as fuel to empirical verification. In particular, combustion of alloys took place both in the solid state and immediately after they were sprayed in a liquid state. In the first case a double cone was used to reduce the sediment left on the walls by the nonvolatile combustion products. The inner cone was latticed, and bunsen burners were placed in the space between the cones.

Since the gas entered the inner cone through lateral orifices, a certain part of it remained completely clean. The overall sediment left on it was reduced from 23% of the mass of all the combustion products to 13%. Tsander thus made every possible experimental, as well as theoretical effort to give foundation to his idea of using metallic fuel. In his article he also discussed other means of using metals, in particular through combustion immediately after evaporation, and use in the form of powder or powder mixed with another substance. Tsander mentioned the use of plastics as solid fuel, and emphasized the fact that they yield volatile combustion products. Finally the rocket scheme consisting of a large central rocket surrounded by numerous lateral liquid propellant containers was mentioned. The article was closely connected with Tsander's lecture to the Commission on Scientific Aeronautics, delivered on 30 November, 1928.**

Tsander also worked on metallic propellants at GIRD, and while there developed a design, which unfortunately is not preserved in the archives, for a metallic-propellant rocket.† Metallic fuel was also proposed for an engine with a thrust of 600 kg.††

In conclusion, several foreign companies are presently developing solid-propellant jet engines, including an engine using powdered magnesium as one of its fuel components.‡

JET ENGINES

Tsander devoted a great deal of attention to jet engines. The text of the lecture he wrote in 1923‡‡ refers to the installation of a jet engine in a spaceship, and to its use as a propulsive force in the lowest layers of the atmosphere, This is also discussed in the article "Perelety na drugie planety."

In the article "Sravnenie raskhoda topliva dlya sluchaya, kogda kislorod beretsya iz atmosfery, i dlya sluchaya, kogda on zapasen v rakete" (A Comparison of Fuel Consumption in the Cases When the Oxygen is Obtained from

* Tsander, F.A. "Problema poleta...." (The Problem of Flight...), p. 17. 1947. The article was first printed in "Raketnaya tekhnika," No. 5, pp. 91-100, Moskva-Leningrad, 1937, and was reprinted in 1947 and 1961.

** Tsander, F.A. "Problema poleta...." (The Problem of Flight....), p. 17. 1947.

† Tsander, F.A. "Problema poleta...." (The Problem of Flight....), p. 67. 1961.

†† Ibid., pp. 65-66.

‡ Mazing, G.Yu. "Vozdushno-reaktivnye dvigateli" (Jet Engines), p. 67, Moskva. 1961.

‡‡ [See third footnote on p. 135.]

the Atmosphere and when it is Stored in the Rocket)* Tsander showed the superiority of craft which take air from the surrounding medium.

In the table of contents of the book presented to Glavnauka in 1927, the calculation of jet engines "with piston or turbine compressor," as well as with an injector, is mentioned.

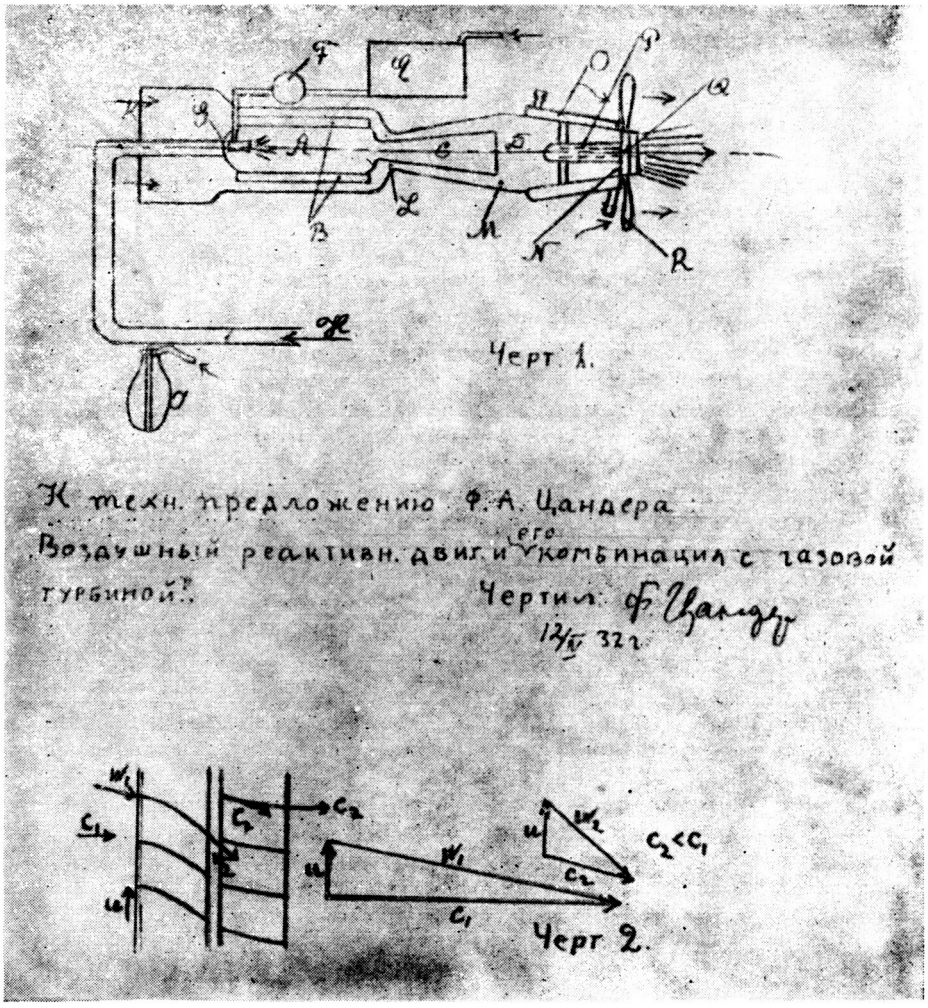

FIGURE 3. Illustration for Tsander's proposed scheme of a "Jet engine and its combination with a gas turbine"

Tsander wrote extensively about jet engines in the book "Problema poleta pri pomoshchi reaktivnykh apparatov." In this book various designs for jet engines and jet superchargers were proposed, and special thermal cycles for increasing the exhaust velocity of combustion products from the

* Tsander.F.A. "Problema poleta...." (The Problem of Flight....), p.261. 1961. First printed in "Raketnaya tekhnika," No.5, pp.111-115. Moskva-Leningrad. 1937.

nozzles of jet (and liquid-propellant) engines were discussed, and their theory given. Practically they were realized by means of straight and inverted cones, the latter of which required intense cooling. In one paragraph dealing with the efficiency of various types of jet machines Tsander devoted considerable attention to jet engines; for example, he wrote that using the first stage of a multistage rocket as fuel might become unnecessary in the course of time, when the steady improvement of jet engines and the combination of propeller engines with rockets would make it possible to leave the earth with greatly reduced consumption of solid propellant, or none at all.*

Tsander envisaged the combination of jet engines with liquid-fuel rocket engines, which is a topical problem at the present day.** Section H, item d, of Tsander's program in the book "Raschet reaktivnykh dvigatelei i ikh kombinatsii s dvigatelyami drugikh vidov"† reads: "The flight of rocket-propelled airplanes with jet engines, taking all of their air from the atmosphere while still on the earth, and using increasingly more liquid oxygen as their altitude increases."

Fridrikh Arturovich attributed great importance to the use in jet engines of turbines such as are nowadays widely used in gas turbine engines. Section "G" of the program mentioned above bears the heading, "Combinations of turbines with jet engines." An unpublished sketch "K tekhnicheskomu predlozheniyu F. A. Tsandera. Vozdushnyi reaktivnyi dvigatel' i ego kombinatsiya s gazovoi turbinoi"([Illustration] to F. A. Tsander's proposed jet engine and its combination with a gas turbine), (Figure 3), dated 12 April, 1932, has been preserved.††

SPACE FLIGHT

Fridrikh Arturovich devoted a number of papers to the subject of space flight. Almost all of the papers discussed below were published in 1961,‡ although the majority of them were deciphered by Tsander as early as 1924 (the latest dates of decipherment are in 1925). Slides (for example, Figures 4 and 5) were made from some of them, and many are mentioned in the table of contents of the book "Polety na drugie planety i na Lunu" (in the chapter "Raboty avtora" (Papers of the author)), written in 1925; all are mentioned in the table of contents of the book "Perelety na drugie planety; pervyi shag v neob'yatnoe mirovoe prostranstvo," which Tsander presented to Glavnauka in 1927.‡‡ It is possible that more studies on this subject will come to light when Tsander's scientific works are fully appraised.

In the article "Opredelenie putei pereletov, dobavochnykh skorostei, kotorye dolzhny byt' soobshcheny raketoyu mezhplanetnomu korablyu i prodolzhitel'nosti pereletov" (Determination of Flight Duration and of the

* Tsander, F.A. "Problema poleta ..." (The Problem of Flight...), p.47. 1932.

** Express-information, AN SSSR, No.6 (36), No.4 (24). 1963.

† Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p.457. 1961.

†† Tsander archive.

‡ Tsander, F.A. "Problema poleta..." (The Problem of Flight...), pp.285-381, 429-435. 1961.

‡‡ Ibid., pp.444-455.

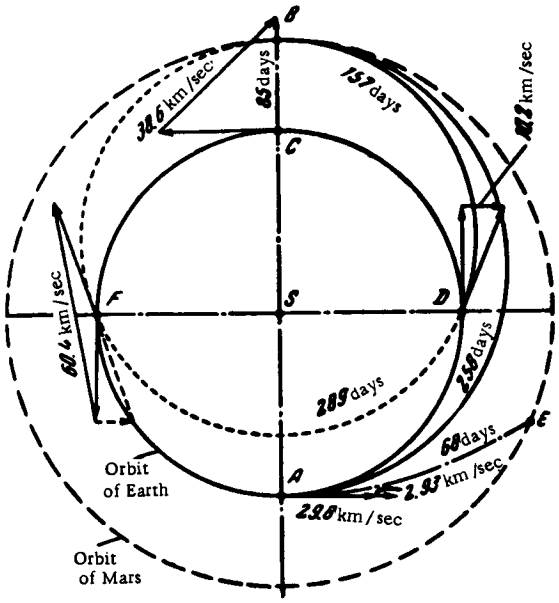

FIGURE 4. Trajectory of a flight from Earth to Mars with corresponding additional and total velocities of the spaceship

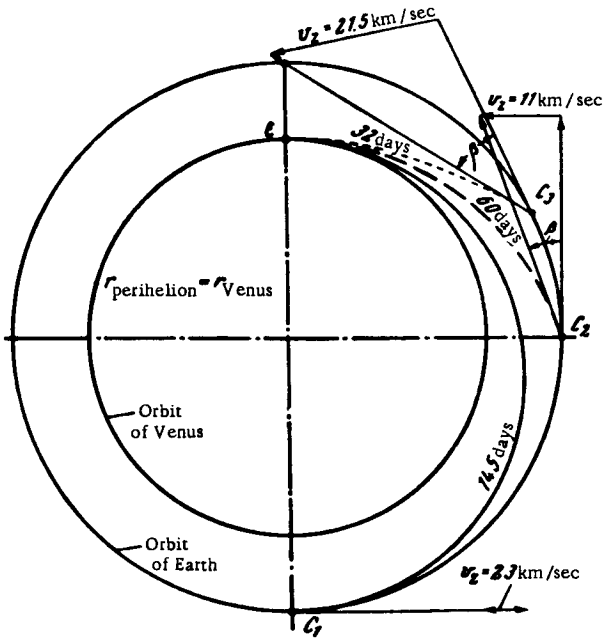

FIGURE 5. Trajectory of a flight from Earth to Venus with corresponding additional and total velocities of the spaceship

Flight Paths and Additional Velocities that must be Imparted to a Rocket-Propelled Spaceship), in which Tsander calculated trajectories for flights to other planets, and the corresponding times and velocities, he devoted special attention to the question of the energetic efficiency of different trajectories.* Considering the orbits of the planets, in the first approximation, as circles lying in a single plane, he emphasized the importance of semielliptical trajectories which touched the planetary orbits at aphelion and perihelion. The results of Tsander's calculations for Mars and Venus can frequently be found in contemporary literature on the subject (although the figures do not coincide, the correspondence is quite good). Fridrikh Arturovich pointed out further that "in the case of elliptical orbits (of the planets — A. Ts.) such mutual positions of the planets can be found as will permit some reduction in the length of path and duration of flight. The mutual inclination of the planetary orbits requires that the rocket be given some additional velocity perpendicular to the plane of the orbit of the launching planet."**

It must be added that Tsander's plans included publication of approximate, as well as more precise calculations. In the table of contents of the book presented to Glavnauka in 1927, one of the sections was headed: "Bolee tochnoe issledovanie putei pereletov, dobavochnykh skorostei i nachal'nykh vesov mezhplanetnogo korablya a) prinimaya, chto orbity obeikh planet — ellipsy, b) v uchastke deistviya dvukh nebesnykh tel" (More exact study of the flight paths, additional velocities, and launching weights of spaceships a) supposing the orbits of both planets to be ellipses, b) in the area of influence of the two heavenly bodies."

Nowadays energetic efficiency is also considered one of the factors influencing the choice of an actual trajectory (all of the requirements cannot be satisfied simultaneously); in particular, this factor is connected with the choice of a launching date.

Tsander's paper "Kogda mozhno letet' na druguyu planetu ekonomnoi skorost'yu i kogda net. V kakoe vremya pri etom proiskhodit pribytie" (When it is Possible to Fly Economically to Another Planet and when Not. Time of Arrival).† is devoted to launching dates. In it he considered the relative positions of the planets of departure and arrival and of the sun which would make possible flight with additional velocities not exceeding the prescribed limit of 8 km/sec.

Nowadays, great importance is attributed to the correction of spaceship trajectories. Tsander also conducted theoretical research on this subject: "Korrektirovanie poleta pri priblizhenii k planetam s tsel'yu dostizheniya bezopasnogo spuska v zhelaemom meste" (Flight Correction Approaching Planets with the Object of Landing Safely in the Place Desired) and "Opredelenie neobkhodimoi dobavochnoi skorosti dlya dostizheniya zhelaemogo izmeneniya puti" (Determination of the Additional Velocity Required for a Desired Change in Path). In the first paper Tsander particularly touched on the question of how a cosmonaut can determine the orbit of his spaceship when approaching a planet. Fridrikh Arturovich came

* In 1925 Hohman published some of his research on this subject. Tsander also illustrated his corresponding calculations by slides in lectures, beginning in January, 1924.

** Tsander, F.A. "Problema poleta..." (The Problem of Flight...), pp. 295-296. 1961.

† In the 1961 edition the title was somewhat altered. See Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p. 316. 1961.

to the conclusion that for this purpose it was enough to measure three quantities – the angular diameter of the planet, the velocity of its change, and the angle between the velocity vector and the straight line joining the spaceship and the center of the planet. The remaining quantities characterizing the orbit can be computed.

Tsander's subsequent papers are concerned with flight around planets or their satellites: "Izmenenie puti poleta vokrug Solntsa deistviem planet" (Change in the Path of Flight around the Sun Due to Planetary Influence), "Prirashchenie kineticheskoi energii ot obleta planety" (Increase in Kinetic Energy from Flight Around a Planet), and "Ogibanie Luny s tsel'yu maksimal'nogo uvelicheniya ili umen'sheniya skorosti peredvizheniya" (Rounding the Moon for Maximum Increase or Reduction of Velocity). Tsander's calculations led him to the conclusion that flight around a planet or its satellite would impart additional energy to the spaceship. He illustrated this idea in his lectures by means of slides. Tsander also wrote a paper entitled "Raschety poletov v mezhplanetnoe prostranstvo s vozvrashcheniem posle ogibaniya planet na zemlyu" (Calculations of Flight into Outer Space with Return to the Earth after Orbiting the Planets).*

In the article "O vygodnosti uskoreniya mezhplanetnogo korablya deistviem rakety v momenty, kogda skorost' poleta – bol'shaya" (The Advantageousness of Accelerating a Spaceship by Rocket Action at Moments of High Flight Velocity) Fridrikh Arturovich showed that from an energetic point of view, it was advantageous to accelerate a spaceship when it passed close to a planet. He presented this article to Glavnauka in 1926. Finally the paper "Opredelenie putei dlya poletov v mirovoe prostranstvo s vozvrashcheniem na Zemlyu cherez tseloe chislo let" (Determination of Paths for Flights into Outer Space with Return to the Earth After a Whole Number of Years).

In studying the many problems of space flight, Tsander was the first in the history of science to apply a method of approximations, according to which the path followed by the spaceship was by convention divided into the spheres of influence of different planets or their satellites. It was assumed that in the sphere of influence of each planet (or satellite) other heavenly bodies did not affect the movement of the spaceship relative to that planet (or satellite). This permitted simpler problems to be substituted for the complicated problem of three or more mutually attracting bodies.** Interestingly enough, not until 24 years after Tsander's death did V. A. Egorov apply this method to the boost and braking of the spaceship Luna.† Tsander's work on determining the spheres of influence of planets or their satellites was also reflected in his own short manuscripts "Opredelenie vremeni, neobkhodimogo dlya dostizheniya dannogo malogo rasstoyaniya ot dannoi planety" (Determination of the Time Necessary to Reach a Given Small Distance from a Given Planet) and "Opredelenie rasstoyaniya ot dannoi planety, dlya kotorogo prityazhenie solntsa i prityazhenie planety nakhodyatsya v dannom otnoshenii drug k drugu" (Determination of the Distance from a Given Planet for which the Attraction of Sun and Planet will have a Given Ratio).

* From Tsander's appeal to Glavnauka, 8 October, 1926.

** A similar method has been used previously in astronomy, but Fridrikh Arturovich applied it to the movement of a spaceship.

† Egorov, V.A. "O nekotorykh zadachakh dinamiki poleta k Lune" (Some Problems in the Dynamics of Flight to the Moon).– Uspekhi fizicheskikh nauk," Vol. XIII, No. 1a. 1957.

For flight in outer space Tsander suggested several new methods which are not expedient for ascending flight from the earth, but in general are definitely superior to ordinary thermochemical rockets for flight in outer space itself. In the article "Perelety na drugie planety," for example, Tsander wrote: "If solar light strikes a mirror, a screen, or dust particles, it exerts a definite pressure. In the enormous distances of interplanetary space small forces impart comparatively great flight velocities."* Nowadays this view is generally recognized; all engine designs that yield low acceleration are designated for use in outer space itself. In Tsander's day another point of view was encountered; for example, in the article "O primenenii tonchaishikh listov dlya poletov v mezhplanetnom prostranstve" Tsander opposed the ideas of Perel'man, who, as Tsander wrote, "analyzes the possibility of flight to other planets using very thin mirrors..." but "...in doing so makes no distinction between flight from the earth to the extent of orbiting the globe and flight in interplanetary space itself."**

Tsander devoted the papers "O primenenii tonchaishikh listov dlya poletov v samom mezhplanetnom prostranstve" (The Use of Very Thin Sheets for Flights in Outer Space) and "O davlenii sveta na kombinirovannye zerkala" (Light Pressure on Composite Mirrors) to theoretical studies of flight by means of light pressure.†

Furthermore, Fridrikh Arturovich was the first to propose increasing rocket performance, for flights in interplanetary space, by means of mirrors which concentrated solar light in a definite place in the spaceship.††

Both proposals were reflected in the table of contents of the book "Polety na drugie planety i na Lunu," which Tsander began to write in 1925. He entitled one of the chapters of the book "O dostizhenii drugikh solnechnykh sistem vnutriatomnoi energiei ili v spetsial'nosti energiei razlozheniya radiya" (Reaching Other Solar Systems by Means of Atomic Energy or, in Particular, by the Energy of Radium Disintegration).

Some more information about the papers on space flight methods outlined (and possibly also completed) by Tsander is found in the table of contents of the book he presented to Glavnauka in 1927. For example, Tsander wrote about flights "using systems of mirrors and light-trapping prisms," about the use of machines to convert solar rays into low-velocity cathode rays, about space flights "by the pressure of cathode rays emitted by the spaceship itself,"‡ and about research "on the usefulness of machines to convert solar energy into other forms of energy for space goals."‡‡

* Tsander, F.A. "Perelety na drugie planety" (Flights to Other Planets). Tekhnika i zhizn', No.13, p. 16, 1924.

** Tsander, F.A. "Problema poleta..." (The Problem of Flight...), p. 361, 1961. As is evident from the text, and in particular, from the words "as I shall show in a special article" (p. 362), part of Tsander's article was mistakenly placed under the heading "Editor's Note."

† The titles have been taken from the inventory compiled when Tsander's widow transferred his papers to GIRD, and kept in his private archive. The last of them is the same as the title of a paper of Tsander's on the same subject, printed in 1961 (Tsander, F.A. "Problema poleta...." (The Problem of Flight...), pp. 376-381. 1961). Others of the published papers probably correspond to the first title (ibid., pp. 361-381); however, Tsander's papers on the use of light pressure have not been published in their entirety, as appears from comparison of the published material with the corresponding slides.

†† At the end of Tsander's autobiography, published by Professor Rynin, there was an incomplete list of proposals which Tsander considered to have originated with him. They include the idea of imparting additional energy to a spaceship by orbiting planets, the idea, given above, of increasing rocket performance by means of mirrors concentrating the solar light, a proposal to build a finned spaceship, and others.

‡ Tsander, F.A. "Problema poleta...." (Problems of Flight...), pp. 447, 451. 1961.

‡‡ Ibid., p. 454.

Tsander's proposals for the use of light pressure and the energy of light rays gathered at a definite place on the spaceship by means of mirrors are now discussed in print, and there exist corresponding contemporary projects.*

An engine whose thrust is obtained from cathode rays is related to what in modern terminology are called electric thrust engines. It is true that the idea of obtaining thrust from cathode rays or even α-particles remained undeveloped because of the relatively small mass of α-particles and the even smaller mass of electrons, but the notion of using charged particles to creat thrust in space is nowadays widely discussed and many designs making use of the latest accomplishments of physics incorporate it.**

Tsander also worked on the shielding of spaceships from meteors,† and the living conditions of cosmonauts in flight and on other planets. He designed a cylindrical space station that would rotate on its axis, and illustrated it with a slide in lectures and reports.

Fridrikh Arturovich also worked on problems nearer to realization than flight to other planets. His calculations of the flight of long-range rockets beyond the atmosphere belong to this category. Evaluating the importance of his research in this field, Tsander wrote in 1932: "Little has been written about the flight of long-range rockets beyond the atmosphere, but in the immediate future this part of the flight path will play a great role in the rapid transport of cargoes and people, as well as in the firing of missiles from one point on the earth to another through interplanetary space "†† One of Tsander's slides gave a partial illustration of these considerations.

In conclusion let it be said that Tsander, as early as the 1920's, noticed the connection, now obvious and growing stronger every day, between the development of rocketry and a number of other fields of human knowledge. In 1925 he wrote, "The development of science and engineering, and in particular, of achievement in the field of aviation, of radioengineering, Einstein's theory of relativity and the theory of atomic decay, all of which seemed incredible a number of years ago, have gone hand in hand with boldness in thought and the audacity to work out designs for the attainment of other worlds.‡

CONCLUSION

In conclusion I shall touch upon the tribute paid to Tsander's work by both individuals and the public during the last years of his life and immediately after his death.

* For example, the design of the General Electric Company (see, e.g., Levantovskii, V.I. "By Rocket to the Moon" (Raketoi k Lune). Moskva, 1960. p.41), and the design of G. Erike (ibid., p.35).

** Ibid., pp.36-40.

† Tsander, F.A. "Problema poleta...." (The Problem of Flight....), p.429. 1961. (Article: "Ob otklonenii meteorov i zaderzhivanii ikh deistviem elektrostaticheskogo elektrichestva, vypuskaemogo mezhplanetnym korablem" (The Deflection of Meteors and Their Containment by Means of Static Electricity Released by the Spaceship).

†† Tsander, F.A. "Problema poleta...." (The Problem of Flight....), p.58. 1932.

‡ "Polety na drugie planety i na Lunu" (Flights to Other Planets and to the Moon). Introduction. Manuscript, 14 14 August, 1925. Tsander's private archive.

In 1932 K. E. Tsiolkovskii wrote to Tsander, "I thank you for the learned work you have sent me,* for your greetings, and for your fruitful work on astronautics. . ."**

On 13 May, 1933, the Bureau of the Praesidium of the Central Board of Osoaviakhim passed a resolution to perpetuate Tsander's memory in several ways: by giving his name to GIRD, of which he was the founder and director of the chief work team; by widely disseminating in print his work on jet propulsion; by studying, developing, and publishing his papers, etc.

His obituary notice, signed by twenty people, including Tsiolkovskii, reads: "At Kislovodsk, on 28 March at 6 in the morning, the renowned engineer, inventor, and jet propulsion theoretician Fridrikh Arturovich Tsander passed away. On the basis of his theoretical and practical work Tsander founded a school of jet engine theory and design. . . Notwithstanding his weak health, Tsander continually pursued his work at an astounding, truly Bolshevik pace, showing heroic enthusiasm.

"From his pen flowed a number of theoretical works giving the world's only calculations in the field of jet propulsion."†

In the book "Raketnyi polet v stratosfere" (Rocket Flight in the Stratosphere), published in 1934 by Voenizdat, it was written of Tsander that "Thanks to his work over the past 10 years, the prototypes of the first Soviet rocket engines were built.

"F. A Tsander died in 1933, but he left behind him an amiable group of workers, students and followers."

All of Tsander's life was continual fruitful creative work, a struggle for rocketry, scientific and engineering progress, and for the good of mankind. He was a true, selfless son of his country.

* Tsiolkovskii was referring to the book "Problema poleta pri pomoshchi reaktivnykh apparatov." The Problem of Flight by Jet Propulsion), 1932.

** The letter is preserved in the Tsander archive and was published in the magazine "Nauka i zhizn'," No. 10, p. 21, 1961.

† "Tekhnika," 30 March, 1933 (the obituary notice is printed in abridged form).

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F.A. TSANDER'S ENGINEERING CONTRIBUTIONS TO ROCKETRY

(Inzhenernye razrabotki F.A. Tsandera v oblasti raketnoi tekhniki)

When speaking or writing of one's teacher, one desires to show as clearly as possible what chiefly, and what typically, made him a great man. Fridrikh Arturovich Tsander's modesty and charm made him such a lively and interesting person that in describing his life and work not the least departure from objectivity can be made.

It is often said that Tsander was an outstanding Soviet scientist, one of the pioneers in Soviet rocket engineering, whose talent and inextinguishable energy enabled him, in a relatively short life, to advance greatly the science of rocket engines and to show, by experiment and practice, the farsightedness of rockets equipped with liquid-propellant engines.

This is, of course, a correct evaluation of Tsander's activity, but it is impossible to omit mention of his great role in the founding and formation of a Soviet school of rocket engineering. The fundamental principles of rocket design which he laid down were successfully taken up and developed by his students, many of whom soon stood in the first ranks of the army of scientists, designers, and engineers who first stormed the cosmos. In speaking of Tsander, therefore, and of his theoretical and engineering work, mention of the attainments of the followers who successfully realized many of his ideas, cannot be omitted.

Fridrikh Arturovich was a disciple of Konstantin Eduardovich Tsiolkovskii. On Tsiolkovskii's 75th birthday Tsander sent him an autographed copy of the book "Problemy poleta pri pomoshchi reaktivnykh apparatov." He wrote: "... Through the amicable cooperation of enthusiastic people we at GIRD are continuing to do research in the happy domain of astronautics, in which your work first broke the eternal ice which impeded mankind's path to the goal."*

Tsander was at the same time an excellent theoretician and remarkable mathematician, and an engineer, technician, and experimenter. This combination of qualities gave this tireless enthusiast the capacity to make notable contributions to both theory and engineering. He published the fundamental theory and calculations of combustion chamber thermodynamics, and his methods of determining the parameters of combustion products, with and without consideration of dissociation, are familiar.

A. I. Polyarnyi, F. L. Yakaitis, and A. D. Kochuev perfected themethod,

* From Tsander's letter to Tsiolkovskii (Archive of the Academy of Sciences, USSR, Folio 555, inventory 4, file 670).

following Tsander in using the concept of equilibrium constants. This method is universal, and valid for the calculation of any type of fuel and for any conditions, with a high degree of accuracy.

Tsander performed many calculations relating to combustion chamber heating and determined the consumption and velocity of the cooling liquid. The results of his thermodynamic and thermal calculations permitted him to give correctly the basic structural dimensions of the engine in experimental models. Tsander's method of cooling system calculation was quite exact for that time. At present these methods are regarded as approximate, but quite adequate for carrying out several engineering calculations.

Using experimental data and the advances of related science, Soviet scientists have created quite precise modern methods of calculation.

Fridrikh Arturovich devoted a good deal of attention to choice and analysis of the fundamental layout of basic engine accessories. In evaluating one arrangement or another he made use not only of the results of calculations, but also of the logical deductions which a gifted scientist can make from the intelligent use of many theoretical propositions. Tsander had the ability to analyze interdependent processes and to devote deep study to separate, including particular and apparently secondary, questions.

This feature of his creative activity can be illustrated by his choice and analysis of feed systems. In his earliest engineering work he turned his attention to many characteristic features of liquid-propellant rocket engines. Clearly, some loss of energy was necessary in order to displace the fuel components from the tanks into the combustion chamber. The more efficiently the production and yield of this energy were organized, the better the system would be. Tsander proposed using part of the thermal energy produced in the chamber from combustion of the basic fuel, and feeding in the components by means of a turbo-pump.

Tsander built models of the ER-1 jet engine and subsequently, of the more powerful ER-2 and ER-10, which contained progressive features that found practical application and were developed further.

Fridrikh Arturovich did not rest at the solution of scientific research problems. Future flights to Mars, in his opinion, should not only reveal the mystery of the "Red Star" (as he called Mars), but should also strengthen the national economy. He suggested using several types of rockets for study of the upper layers of the atmosphere and, in the event of an attack on the USSR, as military rockets.

Tsander's education was that of an engineer. While working on engine design he did not forget about technological features or questions of manufacture. He took into account manufacturing costs, the difficulty, in those years, of obtaining necessary raw materials, the feasibility of production, and the idiosyncrasies of foremen, mechanics, and metal workers, urging his companions to find ways of lowering production costs.

Tsander was a remarkable experimenter. On a proving ground outside the city he built the USSR's first test stand. Both cold and, in the following years, firing tests were distinguished by exceptionally thorough preparation, and even in the first years, the stands were equipped with many measuring instruments. Tsander also paid great attention to safety engineering, and the very first GIRD stand had a thick concrete wall to give the experimenters secure protection. In GIRD's production shops and laboratories people were carefully shielded from every sort of danger and unforeseen disaster. Thick steel sheets, remote control, and special

protective suits were used just where needed. The conditions of safety engineering were determined through knowledge, such as it then was, of the processes taking place in an engine. The precautions taken were so good that during the entire period of GIRD's research on machines entirely new at that time, not a single case of injury occurred.

The results of experiments were carefully analyzed, as the test records that have been preserved testify, with resulting recommendations that were realized in the preparation of the next experiment. The records were signed not only by Tsander, but also by the others who participated in the conduct of the experiment. Tsander was always supported by the Central Council of Osoaviakhim, the Science and Engineering Council, the party organization, and the Head of GIRD.

In his work Tsander depended on the assistance of many young GIRD experts. His first team included L. S. Dushkin, L K. Korneev, A. I. Polyarnyi, A. V. Salikov, V. Gryaznov, E. K. Moshkin, L. N. Kolbasina, and otners. Many of Fridrikh Arturovich's students and friends were in other teams. I. A. Vorob'ev, E. M. Matysik, P. S. Aleksandrov, B. V. Frolov, K. K. Fedorov, N. N. Krasnykhin, and other mechanics and testers working in GIRD's small production department skilfully resolved complicated questions related to production and other operations. By 1933, for example, they had succeeded in processing high-strength alloyed steel with a high degree of accuracy, and in soldering the combustion chamber in such a way that its seams were not burst by the thermal stresses arising from the liquid oxygen cooling of the superheated chamber. They even succeeded in mastering the welding of aluminum and its alloys, which at that time was one of the most complicated tasks.

Features of the engines computed, designed, and built by F. A. Tsander, results of the calculations he performed and the schemes he worked out, and the accomplishments that have characterized the development of his ideas will now be discussed.

THE ER-1 ENGINE

This was the first Soviet gasoline jet engine. Careful calculations, thermal and others, preceded its construction. Tsander studied the effect of adding oxygen to the air on the combustion temperature, with gasoline used as fuel. The first calculation was performed without considering dissociation and therefore gave higher temperature values. Tsander showed that the transition from an engine running on gasoline and air to one running on gasoline and oxygen results in an increase of gas temperature in the chamber from approximately 2300 to 5000°K. These results induced him to make a more precise calculation taking dissociation into account, and to consider the chamber wall cooling conditions. Taking gas dissociation into account in the first approximation did not change the temperature figure for a gasoline and air engine, but for the case of a gasoline and oxygen engine, the gas temperature obtained was not 5000°, but 3800°K.

This result was comforting, and it was considered possible to proceed to the calculation of more complicated versions. Applying the law of conservation of energy, Tsander determined the exhaust velocity and temperature of the exhaust gases and the dimensions of the nozzle hole,

performing the calculation for pressures of from 3.5 to 11 atmospheres, and obtaining results in good agreement with experimental data.

Using the results of his thermodynamical calculations, Tsander computed the temperature of the combustion chamber walls. Starting with relationships, many of which are obtained immediately, he determined the conditions that would assure the necessary cooling, and used the results of the calculation to work out the temperatures of the chamber walls and the desired geometrical dimensions of the cooling system flow channel.

In the course of his work on the ER-1 Tsander became the first in the USSR to solve the problem, approximately, it is true, of the choice of an optimum combustion chamber volume.

During the period from 1922 to 1929 Tsander evidently performed engineering calculations for the ER-1, determining its fundamental parameters and geometrical dimensions. The engine was built in 1929-1930.

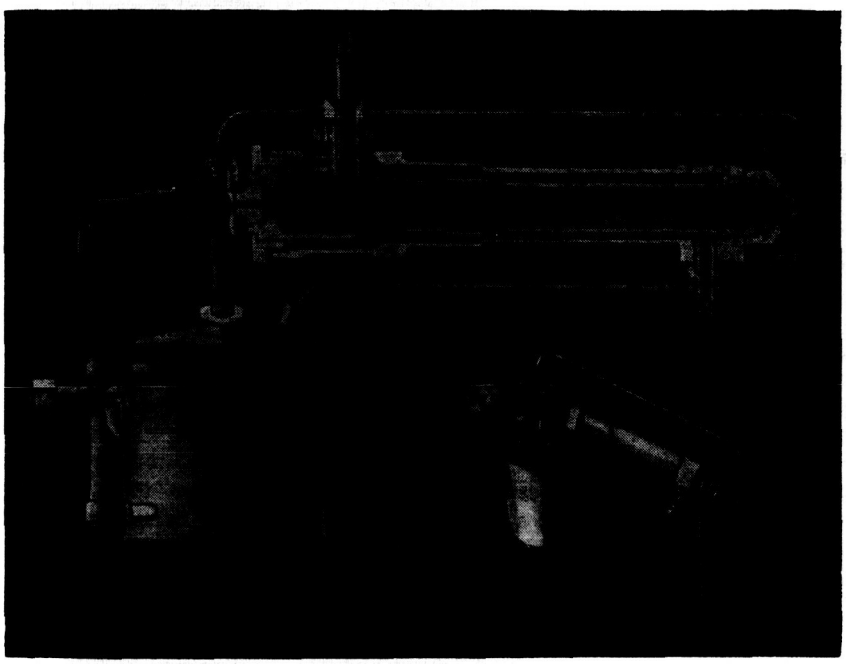

FIGURE 1. The ER-1 engine

It is sometimes said that the ER-1 was a modified blowtorch. This mistaken impression arises from the fact that in building the ER-1 Tsander used some parts of a blowtorch — can with pump and heater – to make a few accessories of minor importance. The fundamental part of the ER-1, its combustion chamber, was designed and built in accord with Tsander's calculations and designs. Figure 1 shows the ER-1 combustion chamber attached to the can into which gasoline was poured. The oxidant, air or a mixture of air and oxygen, entered the cooling system and passed through longitudinal figured slots into the central part of the combustion chamber. Tsander's farsightedness is illustrated by the displacement of the oxidant

into the combustion chamber in gaseous form. Only now is the advisability of introducing the fuel components into the chamber in gaseous form completely clear. Fuel in liquid form was injected into the chamber by a jet atomizer located in the chamber head. The conical nozzle mouth was not cooled. Use of a nonexpansible nozzle permitted evaluation of the parameters of the processes taking place within the chamber with great accuracy, since in building the ER-1, Fridrikh Arturovich wished to verify not only the fundamental principles of jet propulsion, but also the accuracy of his own theoretical calculations. In this engine he studied the possibility of realizing his tempting idea of using structural elements of the rocket as fuel components.

Tsiolkovskii's formula shows that to increase the velocity of a rocket when the engine stops running, the exhaust velocity of the combustion products from the nozzle must be increased, and the ratio of the weight of the rocket, measured at the moment when the engine ceases operation, to its pre-start weight must be reduced, taking into account the weight of added fuel. Combustion of a fuel whose components include several metals must result in increased exhaust velocity, as Tsander thought. If separate structural elements are used as fuel, the weight ratio is reduced. Application of Tsander's idea therefore results in an increase in rocket velocity through two factors. Tsander apparently first expressed the idea of using metal as fuel in 1909.* Throughout his life Fridrikh Arturovich sought means for tne construction of his rocket design. His paper "Primenenie metallicheskogo topliva v raketnykh dvigatelyakh" (Use of Metallic Fuel in Rocket Engines) contains the results of preliminary thermal calculations. Computations indicated that combustion of lithium, aluminum, or magnesium in oxygen would give an exhaust velocity of approximately 5500 to 6750 m/sec. A calculation method for the reactive force obtained from an engine from whose nozzle particles moving at various velocities are ejected, is given. The calculations took into account the possibility of formation of gaseous, as well as solid components. Tsander's paper "Voprosy konstruirovaniya rakety, ispol'zuyushchei metallicheskoe toplivo" (Topics in the Design of Metallic-Fuel Rockets),** in which choice of the most efficient ratio of metal to liquid fuel was considered, is familiar. The ratio of solid and gaseous combustion products was determined. In 1928 Fridrikh Arturovich performed experiments on the manufacture of light alloys containing magnesium and tested their combustibility in air. At this time he came to the conclusion that at least four methods of feeding metal into the combustion chamber must be studied: (1) in the form of ribbons, fed through a special stuffing box; (2) in the form of powder; (3) in molten form; and (4) in suspension, together with liquid propellant. At that time plastic masses were not in widespread use, but even then Tsander proposed that part of his future rocket be made of plastics and used as fuel during flight. This idea, in conjunction with the possibility, which has since appeared, of manufacturing very durable and calorific plastics, acquires special topicality.

GIRD's first team carried out research on the combustibility of metals. The ER-1 was used in the experiments, in which efforts were made to

* See Tsander, F.A. "Problema poleta pri pomoshchi reaktivnykh apparatov. Mezhplanetnye polety " (The Problem of Flight by Jet Propulsion. Interplanetary Flights), p. 150. Moskva. 1961.

** Ibid., pp. 242-260.

introduce magnesium ribbons into the interior of the chamber. Gasoline containing magnesium in suspension was burned and machines to melt metal before its introduction into the chamber were tested. K. K. Fedorov and the author of the present article prepared for testing in the ER-1 a suspension of magnesium in kerosene by means of an electric arc burning in conditions which precluded oxidation of the combustion products.

THE ER-2 and 02 ENGINES

The results obtained from study of jet engine processes in the ER-1 were so significant that Fridrikh Arturovich was able to pass from the use of gaseous air in the ER-1 to liquid oxygen in the ER-2.

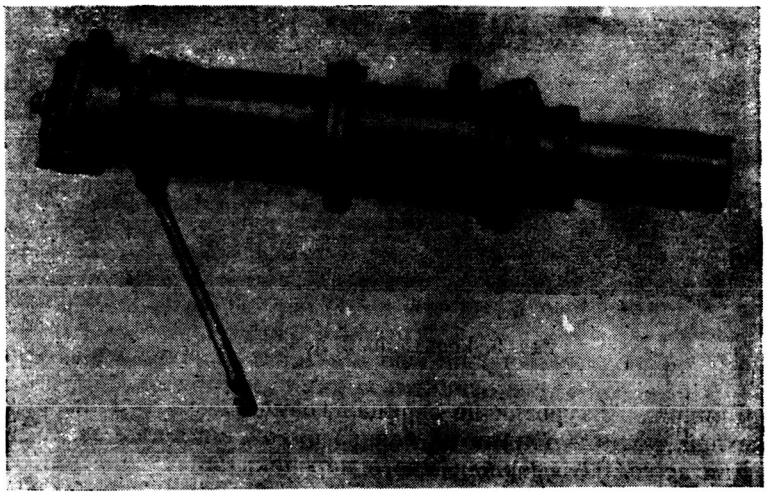

FIGURE 2. The ER-2 jet engine

Tsander believed that liquid-propellant jet engines could be used both in rockets and rocket-propelled aircraft. Rockets are suitable for the transport of cargoes over great distances, for the solution of military problems, and for the investigation of outer space. Tsander proposed the use of rocket-propelled aircraft for human flights, first in the upper layers of the atmosphere, and then in space.

The combination of the aerodynamic qualities of an airplane with the energetic capacity of a liquid-propellant rocket engine gave rocket-propelled aircraft excellent flying characteristics. An aircraft powered by a rocket engine could attain considerable velocity in a short period of time, reach great altitudes, glide for enormous distances, and land like a normal airplane or by means of braking jet engines.

The ER-2 (Figure 2) was designed by Tsander with this future rocket-propelled aircraft in mind. He worked on the design until 1932, when development of the individual components and adjustment of the structural elements was begun at GIRD. At that time it was decided to install the

engine in the RP-1 glider; a fuel feed system was designed, and the first tests were conducted in 1933. The engine was first tested in the form corresponding to Tsander's design, but subsequently his colleagues at GIRD introduced many changes. The ER-2 was developed as a single motor unit incorporating combustion chamber and fuel feed system, but for methodological reasons the construction and operation of the feed system are described separately from the combustion chamber in the article.

The first tests, conducted with kerosene and liquid oxygen, concluded with the bursting of the chamber, and it was therefore decided to substitute ethyl alcohol for kerosene. This backward step was dictated by what were then insuperable difficulties, but the GIRD workers were still attracted, as before, by the main idea of using a high-calorific fuel with a low-boiling oxidant in liquid-propellant rocket engines. In the next versions the walls of the chamber and the interior of the nozzle were smeared with a heat-insulating fire-resistant substance. Some 02 experimental models were built, and means of manufacturing a compound of Al_2O_3 to smear the chamber and MgO for the nozzle were worked out. The choice of the compound's properties depended on the parameters of the processes taking place within the chamber, which were in turn determined by the quality of the propellant and the properties of fuel and oxidant.

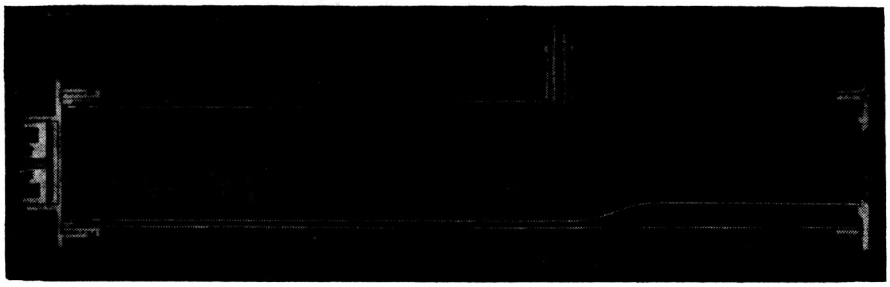

FIGURE 3. The 02 jet engine

Tsander and GIRD's first team, under his direction, considered only a low-boiling oxidant, i. e., liquid oxygen, and not high-boiling oxidants, which then included nitric acid, oxides of nitrogen, and tetronitromethane, more appropriate for the big rockets and spaceships of the future.

In selecting a liquid oxygen-based propellant the GIRD workers based their ideas on the slight prospects of obtaining an increase in specific thrust from a nitric acid propellant. The possibility of attaining this goal with propellant based on low-boiling components, however, was very much greater.

In the light of their experience in the designing and operating of alcohol and oxygen engines, the GIRD workers expected to adopt a propellant consisting of gasoline or kerosene and oxygen, such as is used by many modern engines. Research showed that such engines could conveniently be used both in heavy rockets and in small experimental models.

The next step, in the view of Tsander and his colleagues at GIRD, was to replace gasoline or kerosene by liquid hydrogen.

As early as 1924 he performed calculations for liquid oxygen and hydrogen.* but quite understandably, in the absence of experimental data with liquefied oxygen, it would have been difficult, and perhaps impossible, to go on to the development of engines running on liquefied hydrogen.

Some model hydrogen-oxygen engines are now in operation. The feasibility of using such engines initially in the second and third stages of spaceships, and, in the course of time, also in the first stage, has been theoretically demonstrated. In the future engines operating on liquefied fluorine and its compounds will be familiar.

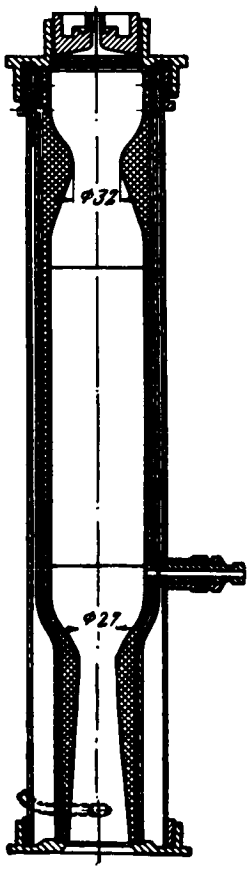

FIGURE 4. 02 jet engine with antichamber

At present, furthermore, many scientists are studying the possibility of building an engine operating on a propellant containing several atomic weights of hydrogen and oxygen; it is well known that the heat generated by the combustion of atomic products is a whole order greater than that produced by the combustion of molecular substances. The solution of this problem, however, is still impeded by great difficulties. One possible solution is the freezing of the atomic products into the components; however, a number of experts still feel that this problem does not even have a real basis.

A no less important advantage of oxygen is its availability from the air in the immediate vicinity of the rocket launching site, while nitric acid must be delivered from plants sometimes at a considerable distance. A deficiency of oxygen propellants, which the proponents of nitric acid pointed out, was their tendency to evaporate and to form ice on the jacket, as a result of which a rocket on oxygen fuel could not long remain in a position of readiness for launching. Even then, however, it was hoped that in the future a cooling coil might be successfully installed inside the oxygen tank, and that rockets ready for launching might be equipped with a hermetically sealed case.

Fridrikh Arturovich did not deny the possibility of using propellants based on high-boiling oxidants. The 02 engine incorporated many farsighted solutions of design problems. Figure 3 shows one version of the combustion chamber with two steel walls. The internal wall, on the side of the gases, had an insulating fire-resistant lining. The fuel entered the hollow interior of the head and was injected into the combustion chamber by a jet atomizer. Liquid oxygen was fed tangentially through two pipes into the lower part of the cooling jacket, and cooled the internal wall of the chamber, while itself being heated and vaporized. Through radial windows in the region of the head it entered the combustion chamber in gaseous form. The second version, worked out later by Tsander's pupils, was distinguished by an antechamber, and is shown in Figure 4.

* Tsander, F.A. "Raschet rakety mezhduplanetnogo korablya" (Calculation of a Spaceship Rocket) (Tsander archive).

Let us consider several of the ideas incorporated in this engine by its designers. The existence of a fire-resistant lining meant that the chamber could be built to take a considerable heat load, but if an insulated chamber were not equipped with external flow cooling, its walls would certainly burst after a certain period of engine operation. The external cooling adopted by Tsander practically assured chamber operation indefinitely. It is interesting to note that until now fire-resistant coverings have been little used, and only now are studies of chambers with a fire-resistant insulated layer between the gases and the internal surface of the walls receiving great attention.

The combustion chamber of the 02 was cylindrical in shape. As subsequent studies showed, this shape is the most successful, although in modern engines the ratio of the chamber's length to its diameter is less than in the 02. This is explained by the high pressures inside the combustion chambers now manufactured, and the improvement of methods for the manufacture of fuel components. The gasification of oxygen in the cooling jacket of the 02, or in some versions, in special vaporizers, must be regarded as an advance, and such a feed system is employed in a number of recent models. It is known that the introduction of gaseous oxygen into the chamber weakens vibrations inside it and improves the combustion process. In the 02 an antechamber was first used, and in one of its models a profiled nozzle was tested. Both of these parts have found the widest application in modern rocket engineering.

In the course of work on the engine a graphite chamber lining was tested. Such chambers ran successfully for up to 60 seconds, but the final version of the 02 was again fitted with a corundum lining in the region of the chamber and a jacket of magnesium oxide in the region of the nozzle. Final tests of this engine showed that it ran well and developed a thrust of 100 kg with a pressure of 11 kg/cm^2 in the chamber.

The construction of the 02 engine was a great triumph of Soviet rocket engineering.

THE 10 ENGINE

At approximately the same period GIRD, under Tsander's direction, built a liquid-propellant jet engine, the 10, for a rocket which was subsequently called the GIRD-X. The 02 engine designated for the RP-1 had to run for a protracted period and was started and switched off many times. In one early version it had to run for 5 minutes. To assure high reliability the structural weight had to be increased. A rocket engine, however, has to run only once and for a considerably shorter time — altogether about 20 seconds — and can therefore be made light. It was originally proposed to use metallic propellant in this engine, but after a series of unsuccessful experiments it was decided to adopt a propellant consisting of gasoline and liquid oxygen.

The chamber shown in Figure 5 was used for testing. Its internal and external walls were made of rust-resistant steel. Unlike the 02, this combustion chamber had only external flow cooling by means of liquid oxygen.

Both components entered the antechamber through a jet atomizer, and ignition was by an electric spark plug. The chamber was pear-shaped (a shape subsequently rejected by Soviet rocket engineers). The nozzle was made expansible, but its angle, as later research showed, was evidently too low.

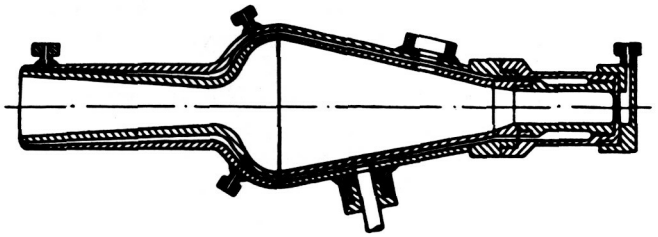

FIGURE 5. Chamber of the GIRD-X rocket

Many deficiencies in the design were made evident by the very first test firings. It was discovered, for example, that the great difference in temperature between the combustion products and the liquid oxygen gave rise to thermal stresses that resulted in the bursting of the chamber. First a crack appeared, and then gases breaking through it from the chamber caused fusion of the metal.

FIGURE 6. The 12k jet engine

At the moment that the crack appeared a sharp drop of pressure in the chamber was observed, and the duct connecting the antechamber with the chamber burst due to the high temperatures. Since simple jet atomizers in the head of the combustion chamber were used, the antechamber was not sufficient to give good mixing of the fuel components and sufficient completeness of combustion. The chamber's operation was unstable, the pressure changed abruptly, there was an audible knock, and the mean value of the pressure did not exceed 2 to 3 kg/cm^2.

After analysis of the experimental data, it was decided to replace the kerosene by ethyl alcohol, as in the 02. At the same time the pear-shaped chamber with the duct was replaced by a cylindrical one. Figure 6 shows one version of an alcohol and oxygen combustion chamber, which proved in

test firings to have insufficient wall cooling. By further work GIRD succeeded in achieving dependable, steady chamber operation and a stable cooling system. Since the time of reliable chamber operation corresponded to what was required, it was decided to install the engine in the GIRD-X rocket.

In testing the 10 and 02 chambers the first team succeeded in obtaining a stable blast at the nozzle throat, with shock waves clearly visible against it. Prominent scientists and experts in gas dynamics and aerodynamics came to GIRD to observe and study what was at that time a new phenomenon.

In evaluating the results obtained by the organization or its individual scientists progress is an important criterion. The chambers built by GIRD scientists were developed further. As an example, Figure 6 shows the uncooled chamber of the 12k jet engine, whose first version was planned and built in 1935. The third and last version ran on 96 % ethyl alcohol and liquid oxygen. The pressure in the chamber reached 14.5 kg/cm^2 and the thrust was 300 kg.

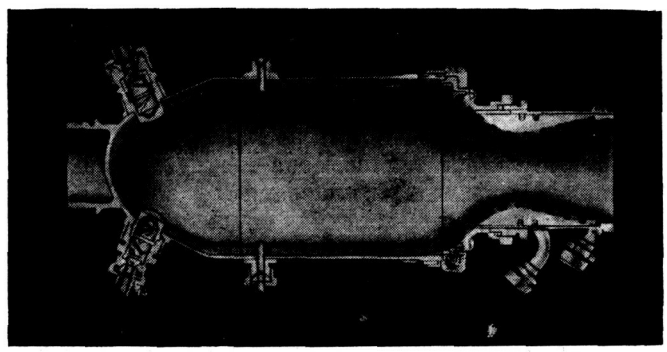

FIGURE 7. The M-29 jet engine

Figure 7 shows the M-29 engine developed in 1938–1939. Here, as previously, both cooling by fire-resistant insulation and by a flow system was used. The engine ran on ethyl alcohol and liquid oxygen and developed a thrust of 200 kg for a chamber pressure of 18 kg/cm^2. Somewhat later, at Moscow, the present author built the E–1 engine along the lines of the 02. The E–1 underwent more than one hundred firings.

COMBUSTION CHAMBER DESIGN

Aside from the metal chambers that underwent test firings, Tsander worked out a number of interesting plans and design sketches, for example, a design for a combined high-power chamber. In order to increase the caloricity of the fuel it was proposed to use metal as a supplement to liquid fuel and air sucked in from the surrounding medium to increase the specific thrust. In the extreme right-hand tank was liquid fuel displaced into the combustion chamber by a pump. The middle tank contained solid metallic fuel. Part of the combustion products, containing the excess

oxidant, was withdrawn from the chamber and directed into a serpentine placed inside the tank. Before their entry into the serpentine, a small quantity of liquid fuel was added to these combustion products to increase their temperature. As a result of the heat exchange between the walls of the serpentine and the metallic fuel the latter melted and entered the combustion chamber in liquid form, being fed by means of an injector. Combustion products leaving that part of the chamber where the highest pressure prevailed were used as the injecting body. The extreme left-hand double tank contained an oxidant— liquid oxygen in its interior section and powdered metal in the outer. The oxygen was pumped into the chamber and the powder was blown in by an injector. In the region of the nozzle was placed yet another, air blast injector designed to suck air in from the surrounding medium.

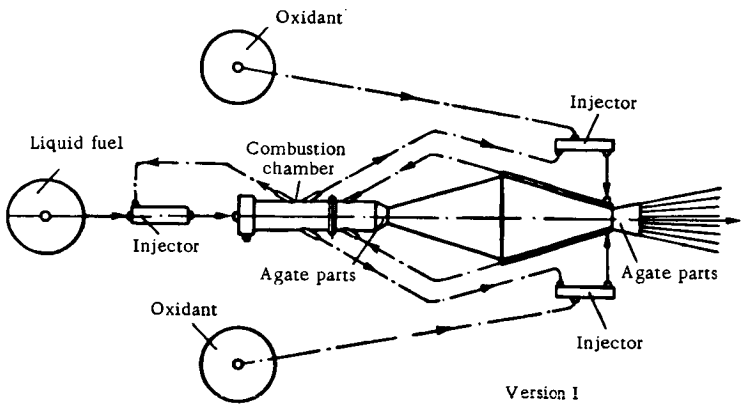

FIGURE 8. Tsander's jet engine with straight and inverted cones and fuel injection

Tsander tried to give form to at least four ideas in his lifetime. He worked on a design featuring a harmonious combination of pump and injector feed, combined fuel (kerosene and metal) and oxidant (oxygen and air), increase of the caloricity of the fuel by the combustion of metal, and increase of the ejected mass through indrawn air.

Pump feeding of the fuel components was soon achieved in practice, but the remaining problems have not been solved and remain topical. The problem of raising the specific thrust by the addition of air to the stream of gases generated in a liquid-propellant rocket engine is of special importance.

The outstanding economy of liquid-fuel jet engines makes their use in big multistage rockets advantageous. An American scheme for a three-stage space rocket planned for launching in 1970, for example, has two stages powered by jet engines. They give boost to the third stage, equipped with a nuclear engine, and bring it to a considerable altitude.

F. A. Tsander theoretically studied and designed an original engine whose chamber was combined with so-called straight and inverted cones. The straight cone, as shown in Figure 8, was not cooled or was not subjected to intensive cooling, while the inverted cone had a forced cooling system. It is known that removal of heat from a supersonic gas flow increases its velocity, and this results in an increase of the specific thrust. Tsander

considered this problem only from a thermodynamic point of view, without taking into account the influences of sudden changes in condensation characteristic of a supersonic gas flow.

Tsander discussed the use of straight and inverted cones with the leading gas dynamics experts of that time. Much work was proposed, but the great volume of his engineering work on the ER-2 and other GIRD models occupied literally all of Tsander's time.

FUEL FEED SYSTEM OF THE ER-2 ENGINE

Tsander devoted great attention to the study of feed systems. The basic idea which he sought to realize in all of his designs consisted of using part of the thermal energy generated in the main combustion chamber for fuel component feeding.

The basic fuel feed system of the ER-2 engine, which was intended for installation in the RP-1 jet glider, consisted of three tanks, a nitrogen balance, vaporizers, a pump, a water tank, pipes, and other parts. Water was chosen as the mass carrier that would transfer the thermal energy from the chamber to the feed system components. The main part of the combustion chamber was here cooled by oxygen, which became gaseous as it moved through the cooling jacket. It is a known fact that the nozzle most often bursts in the region of the throat, since the greatest thermal flow is observed there.

Water was shown to be one of the best liquid coolants. It was evidently for this reason that Tsander chose water as coolant and heat-carrier and used it for heat exchange in the region of the nozzle. The water heated there was transferred to the water tank by means of a pump. From the tank it was sent both to the nitrogen balance and to the vaporizers. In the nitrogen balance heat exchange between the water and the liquefied nitrogen resulted in vaporization of the latter and its entry into the upper chambers of the tanks. The pressure created by the gaseous nitrogen displaced the fuel components into the combustion chamber. In the vaporizers heat exchange also caused gasification of the liquid oxygen. Cold water from the nitrogen balance and the vaporizers again entered the nozzle's cooling jacket.

This scheme was farsighted in its use of the thermal energy generated in the combustion chamber for fuel component feeding; in recent years several other versions of the system have appeared.

The proposals to use liquefied nitrogen and its subsequent gasification, and to employ water and a closed circulating cooling system for the combustion chamber found wide practical application somewhat later, it is true, in a number of different forms.

TURBO-PUMP FEED SYSTEM

For the fuel components to be displaced from the tanks by means of a compressed gas, as in the ER-2 feed system described above, thick-walled tanks had to be constructed. They are highly pressurized and such systems

are therefore called pressure tank systems. As the pressure in the tanks rises, so does their relative weight, i. e., the weight per kilogram of fuel in the rocket. The system's weight ratios are not improved by increases in thrust and dimensions of the rocket. If the relative weight of the feed system is not to increase with the rise of pressure in the chamber, and is to decrease with an increase in thrust, a feed system with balanced tanks must be adopted.

After analyzing the results of his thermodynamic calculations Tsander determined how the thermal efficiency of an engine increases with a rise of pressure in the chamber (and consequently, also in the tanks). He was interested in such powerful engines and big rockets as would subsequently be able to fly to Mars, and he therefore considered fuel injection and pump feeding systems as well as the pressure system of the ER-2.

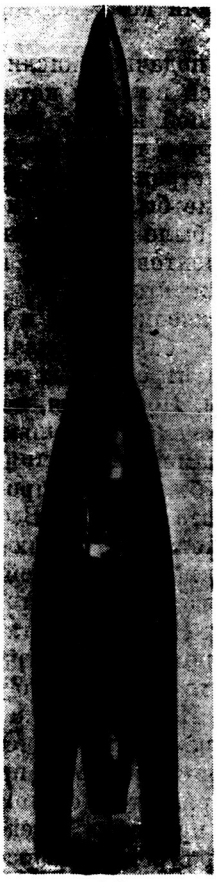

FIGURE 9. The GIRD-X rocket

Figure 8 shows a fuel injection system. Fuel and oxidant were kept in slightly pressurized tanks. This was necessary to overcome hydraulic losses in the pipes running from tanks to injectors and to avoid cavitation. Since the tanks in this system were practically free of pressure, they could be made thin-walled and light. A gas-stream injector was used to introduce the fuel components into the chamber.

Pressure-free tanks were also used in turbo-pump feed systems. The fuel components were fed by means of centrifugal pumps made to operate by a gas turbine, which in turn, according to Tsander, should be made to function by the combustion products striking it after leaving the chamber. The products obtained from combustion of the principal fuel would then be the turbine mass-carriers. All big engines now have such a feed system, except that modern turbines are fed not from the main, but from a special supplementary chamber, which is called the generator. In modern generators the principal fuel has a component ratio which results in generation products of relatively low temperature, allowing reduction of the temperature of the turbine mass-carrier. Sometimes the turbine is fed by the combustion or decomposition of a special low-calorific fuel used to supplement the main fuel. Perhaps the next step in the development of feeding systems will be mastery of the principle proposed by Tsander, i. e., direct turbine feeding from the main combustion chamber.

THE GIRD-X ROCKET

The scientific activity of F. A. Tsander and the GIRD first team was summed up by the launching of the GIRD-X rocket, the first in the Soviet Union to be powered by a liquid-propellant engine. Figure 9 shows a cross-sectional photograph of the rocket, which was built according to sketches that had been preserved. Its

structural form turned out to be so well chosen that it has remained basically unaltered to the present day.

The 09 rocket, built by GIRD's second team, was launched somewhat earlier than the GIRD-X, and used as its fuel consistent gasoline, then called "solid gasoline," which was fed directly into the combustion chamber. The oxidant was liquid oxygen, and oxygen vapor formed by heat exchange with the surrounding medium was used to displace it into the combustion chamber. The GIRD-X rocket was powered by a 10 engine, running on concentrated ethyl alcohol and liquid oxygen. It was constructed of special structural steel and aluminum alloys.

The upper part of the head carried the payload — a parachute with equipment for ejecting it on the upper part of the trajectory. The head envelope consisted of two parts which opened before ejection of the parachute. Modern rockets, of course, also carry their payload in the head and in many cases have a casing which opens. Many modern rockets have "carrier" tanks made in this way. The upper bottom of the oxygen tank had a filler, a safety valve, and a check manometer. The lower part of the compartment contained a "carrier" alcohol tank, while a cylinder of compressed gas — a pressure battery — was placed between the tanks.

The fuel components were displaced from the tanks by gas leaving the battery through a pressure relief valve. Actuating valves were located in the hydraulic connectors between the tanks and the combustion chamber. This "carrier tank" system was known earlier, but it was flight-tested for the first time in the GIRD-X rocket. In time, after familiarity with the operation of turbo-pump feed systems had been achieved, pressurized tank systems came to be rejected.

The engine compartment, with combustion chamber, was located beneath the tank compartment, as in modern rockets. The rocket was equipped with large jet stabilizers such as are found on all modern relatively short-range rockets.

To conclude I shall enumerate some of Tsander's theoretical and engineering accomplishments:

1) creation of a method for the calculation of liquid-propellant rocket engines;

2) research on the operating conditions of liquid-propellant rocket engines;

3) grounds for choosing a rocket fuel based on a low-boiling oxidant;

4) formulation of a basis for experimental study of the processes taking place in liquid-propellant rocket engines;

5) establishment of the requirements for liquid-propellant rocket engines to be installed in airplanes;

6) construction and finishing of a working model of the ER-1 jet engine;

7) engineering development of the 10 rocket engine;

8) engineering development of various types of fuel feed systems;

9) drafting of powerful engines;

10) drafting of turbo-pump feed systems;

11) study of the possibility of using metallic fuels;

12) engineering development of apparatus for study of the feasibility of using separate parts of the engine and rocket structure as fuel;

13) engineering development of a firing stand and of a system for measurement of parameters and remote control;

14) engineering development of the first liquid-propellant rockets.

This is far from being a full list of Tsander's achievements.

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B.N. Vorob'ev and V.N. Trostnikov

Yu. V. KONDRATYUK'S UNPUBLISHED PAPER "TO THEM THAT WILL READ IN ORDER TO BUILD"

(O neopublikovannoi rabote Yu. V. Kondratyuka "Tem, kto budet chitat', chtoby stroit'")

Among Yu. V. Kondratyuk's scientific writings his unpublished paper on space flight* is of special interest. During the most difficult years of the First World War, two revolutions, and the Civil War, he worked on a problem which to the overwhelming majority of people appeared strange, or, at best, very far removed from reality.

Kondratyuk spent sleepless nights on his calculations, trying to neglect nothing which might serve the cause of flight to other planets, and to forget none of the obstacles that man might encounter in his courageous step into space. His paper, exceptionally rich in content and original in its method and the persuasiveness of its proofs, was written completely independently of the few scientists then concerned with rocket flight. It was based on enthusiasm, faith in man's ultimate conquest of the cosmos, remarkable scientific intuition, and outstanding knowledge in the exact sciences and engineering. The paper was completed in 1919, but even when it first saw the light, ten years later, it was an event in the history of rocketry.

The most superficial acquaintance with his first paper of 1916, modified in 1919, shows that the young Kondratyuk was far ahead of the foreign scientists working on rockets and space flight at that time, and took a new forward step in the development of rocketry. His research, carried out after Tsiolkovskii's earliest work, but independent of it, and not duplicating it, provided a final and thorough confirmation of the priority of Russian scientists and engineers in cosmonautics.

Kondratyuk wrote in the foreword to the book published in 1929 that its foundations were laid in 1916. In a letter to N.A. Rynin he referred to the results he had obtained in 1917, but it was not known how extensive an elaboration the original version subsequently underwent. Only comparatively recently did the present authors have an opportunity for careful examination of the original paper, dated 1916 and written in the old orthography, as well as that of 1919 (comprising about three printed sheets, excluding drawings), which was an elaboration of the earlier paper. Both papers were written by hand in school notebooks and carefully preserved by the author.

Detailed acquaintance with Kondratyuk's manuscripts proved a source of great pleasure and a new cause for pride in the gifted Soviet pioneers of

* In 1938 Kondratyuk handed this paper over to one of the authors (B.N. Vorob'ev), dating it 1918-1919, although the exact data of its composition is yet to be verified. The manuscript is now located in the Institute of the History of Natural Science and Engineering, AN SSSR, and all subsequent footnotes will contain page numbers referring to it.

space study. The profound contents and original research method of these manuscripts justify their being regarded as documents of enduring importance in the history of science.

The contents of the 1919 manuscript, which has never been published and has until now been unknown to historians of science and engineering, will here be presented in detail. The manuscript is presently being prepared for publication in a collection of the papers of Russian rocketry pioneers.

The authors have another aim, however, beyond the presentation of an historical document. Kondratyuk's study was written with remarkable conviction that the simplest paths in research could be found by logic and skill. In the knowledge that his work was innovatory, Kondratyuk constantly sought to ensure that readers would not regard it as idle fantasy.

Of an enormous number of calculations and variants only the shortest, most definitive, and readily comprehensible are adduced in the manuscript. In other words, the subject matter is presented in definitive form and in such sequence that the reader is brought step by step to conviction of the correctness and inevitability of the author's conclusions.

The paper of 1919, therefore, independently of its historical and scientific value, is one of the first textbooks on the fundamentals of rocket theory.

BASIC IDEAS

In the foreward to "Tem, kto budet chitat', chtoby stroit'," Kondratyuk wrote: "First of all, in order not be put off by the subject of this paper in itself, or dissuaded of its feasibility, keep in mind that from a theoretical point of view there is nothing astounding or improbable about rocket flight in space."*

In our time, when space flight is a reality, such an introduction would be superfluous, but in those days it was quite different. In giving a full and correct appraisal of the service rendered to science by the first theoreticians of rocket flight we do not always realize how innovatory their contributions to human knowledge were, because, as everyone realizes, rockets were known in the earliest times. However, it must be recalled that steam and its capacity to cause motion (Hero's vanes) were also shown before our era, yet the age of steam began only 250 years ago, and Newcomen, Watt, and Polzunov are rightly considered to be its pioneers. In fact, they were the ones who perceived those properties and potentialities of long-familiar steam that led to the industrial revolution. What was old acquired new significance.

As another example, telescopes were known before Galileo, but only the great Pisan thought of aiming them at the night sky. From that moment the telescope acquired new meaning, and gave final confirmation to the ideas of Copernicus.

It was approximately the same way with rockets. The idea of using rockets for flights to the moon was expressed as early as the seventeenth century,** but until the beginning of the twentieth, it was only one of a

* Manuscript, p. 1.

** Cyrano de Bergerac. "Another World or the Comic History of the Empires and Governments of the Moon." Academia, Moskva-Leningrad, 1931, p. 144.

number of fantastic projects. There was no basis for preferring rockets to other means of flight which people, in their dreams, imagined would take them to the stars. For example, even an author as well-educated and gifted with foresight as Jules Verne described flight to the moon by means of an enormous cannon.

In 1903, Tsiolkovskii's remarkable paper "Issledovanie mirovykh prostranstv reaktivnymi priborami" expressed the conviction that only a rocket would be suitable for space flight. It is really only since the beginning of our century that rockets have come to be regarded by most people as a means of interplanetary travel. Tsiolkovskii's progressive ideas, however, made their way only slowly, and for this reason, Kondratyuk, even though he began his research more than 13 years after the appearance of Tsiolkovskii's article, had to convince his readers afresh that only a rocket would be able to overcome earthly gravity. Besides, as Kondratyuk himself wrote, he could not obtain Tsiolkovskii's article and only heard about it. If Kondratyuk had read this article before 1925, it might perhaps have saved him a good deal of effort and enabled him to concentrate on further development of the ideas of space flight, but since he made his fundamental contributions independently of Tsiolkovskii, we have two approaches to the founding of a theory of space flight, different in method, but equally outstanding.

How did Kondratyuk convince his reader that research should be concentrated on rockets, to the exclusion of other types of craft? He first considered the conditions prerequisite for space flight. It was perfectly clear that at least two conditions had to be satisfied: (1) the flight should not prove fatal for the passengers, and (2) it must be controlled.

To satisfy the first condition, the missile completing the journey must not undergo any significant acceleration, but in order to leave the earth, it must reach a velocity of about 11 km/sec. In order to accelerate the missile to this velocity sufficiently smoothly not to endanger the passengers, it would have to be accelerated along its path for hundreds of kilometers. The construction of a cannon or other stationary instrument (such as a sling) of such dimensions is inconceivable. Even if one might succeed, however, in constructing an electric cannon of such size, the second condition— control— would not be met. A missile launched from such a machine would be the passive plaything of the complicated interaction of planetary gravitational fields, and its crew would be eternally taking leave of the earth. There must be a mechanism to permit changes in course and flight velocity in space, for "in such a new field not everything can be foreseen, and there is nowhere to turn for help in space."*

According to Newton's second law the magnitude or direction of the velocity of a body can be changed when it interacts with other bodies and is repelled, but what is there to repel in airless space? Kondratyuk answered this question laconically and with conviction: "...in the emptiness of space you will find no fulcrum unless you bring it with you."**

A "fulcrum," i.e., some substance that can be used to repel, or can be ejected from the missile, must therefore be taken along to permit change in the direction or magnitude of velocity. This is just the idea of a rocket.

Interestingly enough, Kondratyuk had arrived at the idea of rockets much

* Manuscript, p.3.

** Manuscript, p.4.

earlier by several different paths. This was evidently before he had heard of the contents of Tsiolkovskii's article. This argument is not adduced in the 1919 paper, which is more like a sketch, but is of great interest, and is therefore reproduced here as it was laid out in a letter to Professor N. A. Rynin:

"... having rejected the artillery method as enormously unwieldy and, more important, not assuring return to the earth, which makes it senseless ... I arrived at a combination of the rocket and artillery versions: a cannon shoots a ball, which is itself a cannon, in turn shooting a ball, etc., but this required a starting gun of monstrous size. After this I reversed the muzzle of the second gun, that is, the first ball, making it a regular part of the rocket, and arranged it to shoot smaller balls in the opposite direction [to that of the motion], thereby increasing the active mass of the load at the expense of the passive mass, but the result again was an enormous value for the mass of the cannon. By this point, however, I had already observed that the more I increased the active mass of the load at the expense of the passive mass (balls), the more advantageous were the mass formulas obtained for the rocket. From this it was easy to pass to a purely thermochemical rocket which could be considered a cannon continuously shooting blank charges; after this the fundamental rocket formula was derived..."*

This argument is distinguished by its logic and very clearly characterizes Kondratyuk's scientific method: the transition from the indisputable to the unknown, maintaining at every step the faultlessness and rigor of his reasoning, and keeping his objective constantly in mind. Like the famous argument of Newton, which led from the trajectory of a cast stone to the movement of the moon, Kondratyuk's logical chain leading "from cannon to rocket" seems, once it has been read through, to suggest itself.

It was thus concluded that if the earth's gravity was to be overcome, it might be done only by means of a machine making use of reactive force. In his paper of 1919 Kondratyuk does not discuss why it is disadvantageous to shoot "balls" out of the rocket, and why the best method is to eject incandescent gases, i.e., "blank charges." He had made that calculation earlier, and in the manuscript, taking it as given, he proceeds to the fundamental rocket formula.

THEORETICAL FORMULA FOR THE WEIGHT OF A ROCKET

The fundamental formula giving the weight of fuel needed to accelerate a rocket to a given velocity in empty space where gravity is absent can be derived from various premises, which are, however, always based on the law of conservation of momentum. Tsiolkovskii himself, who first derived this formula (as a result of which it is called Tsiolkovskii's formula), based his work directly on this law and equating the momentum of the ejected gases to the increase in momentum of the rocket, obtained

* Yu.V. Kondratyuk's Autobiography, in Rynin, N.A. "Teoriya kosmicheskogo poleta" (Theory of Space Flight), p.343. Leningrad. 1932.

the differential equation

$$V\,dm = m\,dv,$$

where V is the relative exhaust velocity of the gases (i.e., the velocity of the gases leaving the nozzle, relative to that of the rocket); v is the velocity of the rocket, and m, the mass of the rocket. Using the same principle, Enzo Peltri, whose work will be discussed in more detail below, derived the rocket formula in 1913; and Goddard, in the same year, obtained it by an analogous method, for a solid-propellant pyrotechnic rocket.

Kondratyuk, however, derived the fundamental formula in an original way. First of all, he did not begin directly with the law of conservation of momentum, but with the following assertion: "when two bodies repel each other, the energy (living force) relative to their common center of gravity is divided between them in inverse proportionality to their masses."* Remaining true to his manner of maximum brevity, Kondratyuk neither clarifies nor proves this statement.

It is interesting that the fact of the division of the energy in inverse proportion to the masses is little emphasized in physics textbooks. It is pointed out everywhere, for example, that when an object is shot from a gun the momentum of the gun is equal to the momentum of the projectile, but the simple and useful calculation of what proportion of the energy of the explosion is retained by the gun, and what carried off by the projectile, is seldom presented concurrently. In practice, when students of the Technical Service School were questioned about this calculation, hardly any could give an immediate correct answer, and about half of them first replied that the energy was divided equally. Only after some thought, or after making calculations on paper, did the students come to the conclusion that insofar as the momentum of gun and projectile were equal, their velocities were inversely proportional to their masses, and since kinetic energy consists of half the product of momentum and velocity, it will be proportional to the respective velocities of gun and projectile, i.e., inversely proportional to their masses. Because of this it is desirable to make the gun heavy so that the projectile will carry off nearly all the energy.

Use of this initial assumption about the division of energy, i.e., a veiled form of the law of conservation of momentum, enabled Kondratyuk to avoid such a magnitude as the exhaust velocity of the gases, which could be found only from a special reference book, or through a rather complicated calculation, again requiring such special data as Boltzmann's constant, etc. Kondratyuk expressed the fundamental rocket formula through such a generally known quantity as the heating power or caloricity of the fuel. It cannot be denied that in this form the rocket formula serves better as a base for speculation or practical calculation than in a form connected with the exhaust velocity. The principle of the inverse proportionality of imparted energy and mass seemed to Kondratyuk to follow so readily from the law of conservation of momentum that he considered it unnecessary to derive it, hoping that any interested reader would be able to do it for himself. The characteristics of Kondratyuk's presentation thus appear at the very beginning of his manuscript: he uses all possible means to arouse the reader's mind, reveal relationships new to him, but easily demonstrable, and develop in him engineering and physical intuition.

* Manuscript, p. 8.

Assume that h grams of a fuel with heating power p are burned. The amount of energy liberated is equal to ph. By the principle of the division of energy, mentioned above, the share of a rocket of mass $(m-h)$ is found to be

$$ph\,\frac{h}{(m-h)+h} = \frac{ph^2}{m}\text{ ergs.}$$

This is exactly the fraction of the total energy of combustion corresponding to the ratio of the mass of the ejected gases to the combined masses of gases and rocket.

The energy obtained by the rocket is added to its kinetic energy relative to the common center of gravity, i. e., the rocket receives a supplementary velocity Δv which satisfies the relation

$$\frac{m(\Delta v)^2}{2} = \frac{ph^2}{m} \quad \text{or} \quad h = \frac{m\Delta v}{\sqrt{2p}}.$$

This equation shows that to increase the velocity of the rocket, where the combined mass of rocket and fuel is m, by Δv, $\frac{m\Delta v}{\sqrt{2p}}$ grams of fuel must be consumed. After this the mass of the rocket will equal

$$m - \frac{m\Delta v}{\sqrt{2p}} = m\left(1 - \frac{\Delta v}{\sqrt{2p}}\right).$$

To put it differently: after increase of the velocity of the rocket by Δv by consumption of fuel with caloricity p the mass of the remaining rocket will be reduced and will constitute the $\left(1 - \frac{\Delta v}{\sqrt{2p}}\right)$-th part of the initial mass. The fraction is evidently independent of the mass. This is in agreement with common sense: more fuel must in fact be consumed in order to impart to a heavy rocket the same increase in velocity as to a light rocket. In both cases (heavy and light rocket) the fraction of the general mass which must be consumed in order to increase the velocity by a definite amount is one and the same. This almost obvious reasoning leads directly to the fundamental rocket formula.

Suppose that it is desired to increase the velocity of the rocket by $v = N\Delta v$. Then the combustion of portions of fuel, after each of which the velocity will be augmented by Δv, will have to be repeated N times. Each time the ratio of the weight of what is left of the rocket to the weight of the rocket with the consumed portion of fuel will be the same: $1 - \frac{\Delta v}{\sqrt{2p}}$. The ratio of the weight of what is left of the rocket after the successive acts of combustion to the initial weight will therefore be

$$\frac{m_{\text{fin.}}}{m_{\text{init.}}} = \left(1 - \frac{\Delta v}{\sqrt{2p}}\right)^N.$$

Substituting

$$\Delta v = \frac{v}{N}$$

now gives

$$\frac{m_{\text{fin.}}}{m_{\text{init.}}} = \left(1 - \frac{v}{\sqrt{2p}} \cdot \frac{1}{N}\right)^N.$$

Suppose that fuel is consumed continuously, implying that the portions taken become successively smaller and smaller, while their number grows

without limit. Then the preceding formula tends to a limit as N goes to infinity. This limit is familiar from mathematical analysis, and is equal to $e^{\frac{-v}{\sqrt{2p}}}$, where e = 2.7182818, the base of natural logarithms. Using the limiting value, we can write

$$m_{\text{init.}} = m_{\text{fin}} e^{\frac{v}{\sqrt{2p}}}.$$

This is an interesting derivation of the fundamental rocket formula, in which it was unnecessary to solve the differential equation, which is usually required, but knowledge of a special limit was called for instead. From the point of view of the principle "introduce no complications if they can be avoided by what is less complicated" Kondratyuk's method has no apparent superiority. The choice of this method could hardly have been influenced by considerations connected with the author's knowledge, because it is known that when he wrote the paper of 1916 to 1919, Kondratyuk was fully capable of using higher mathematics, so that a very simple differential equation could hardly have presented any difficulty for him. Furthermore, in preparing the 1929 edition, Kondratyuk again chose to derive the basic rocket formula by means of the special limit. In fact, Kondratyuk simply found such an approach to derivation of the formula essentially more interesting. The fact that combustion of the same fraction of the total mass was required for a determined increase in velocity; that, consequently, the portions of fuel consumed would be in geometrical progression, since the weight of the portions burned would decline with overall fuel consumption; that the ratio of final to initial mass of the rocket would be equal to the weight ratio at every stage, repeated (raised a power) as many times as the number of elementary combustions taking place, was very impressive and persuasive. After making this deduction in 1916, Kondratyuk was keenly aware of the physical processes involved in rocket operation and naturally wished to communicate this vivid feeling to his readers. For this reason he retained his deduction of the fundamental formula by proceeding to the limit in later editions of his papers.

After obtaining the formula for rocket motion in empty space, Kondratyuk remarked that theoretically any velocity can be communicated to a given mass, however low the caloricity of the fuel. For this purpose it is necessary only to take the initial combined mass of rocket and fuel sufficiently great. However, Kondratyuk also observed that the starting mass of the rocket increases very rapidly (as an exponential function) with velocity and that the practically attainable limits can easily be exceeded.

Since the formula just derived does not take into account the earth's gravity it must be made more precise, and Kondratyuk therefore immediately proceeded to derive a formula of rocket flight in the earth's gravity field. He had to modify very slightly the formula obtained earlier, taking into account that the engine now had not only to overcome the inertia of the rocket, that is, to accelerate it, but also to overcome terrestrial gravity. This is essentially equivalent to a reduction in the caloricity of the fuel.

The numerical effect of this reduction will now be calculated on the assumption that the force of gravity is constant, i. e., neglecting the fact that the rocket is moving into regions of space where the earth's attraction is weakened.

Let the acceleration communicated to the rocket by the engine be k times the acceleration due to gravity. Kondratyuk considered two major possible directions of motion, since different formulas are obtained for the two cases.

a) The rocket leaving the earth follows a vertical trajectory. In this case the engine thrust and the force of gravity act in opposite directions. The actual acceleration communicated to the rocket will therefore be equal to $g(k-1)$, i.e., $\frac{k}{k-1}$ times less than the acceleration communicated, under the same conditions, to a rocket outside the gravity field. This means that the velocity acquired through acceleration at every moment, on a rocket in the earth's gravity field, will be $\frac{k}{k-1}$ times less than on a rocket outside the field, i.e., obeying the formula derived above. For flight by the first method, therefore, the velocity in the fundamental formula must be changed to $\frac{vk}{k-1}$. If, in fact, the quantity of fuel, for the case where gravity is present, is reckoned as if there were no gravity, but instead with the velocity v multiplied by $\frac{k}{k-1}$, v appears in the result. The formula for ascending vertical flight in the earth's gravity field can conveniently be written

$$m_{\text{init.}} = m_{\text{fin.}} e^{\frac{v}{\sqrt{ep}} \frac{k}{k-1}}.$$

The exponent contains what Kondratyuk called the "unpleasant" factor $\frac{k}{k-1}$, which increases the quantity of fuel required to reach the necessary velocity.

This expression shows that the effect of the undesirable increase in the exponent can be reduced by taking large values of k. In the limit, when k is very great compared with unity, i.e., when the rocket is accelerated enormously rapidly, the formula for weight of the rocket will be the same as in the case of empty space. To clarify: when the acceleration is very great the rocket almost instantaneously gains the necessary velocity and the fuel consumption that must occur during the period of acceleration to "neutralize" the gravity of the earth has no opportunity to become great. On the other hand, when k is near to unity flight is practically impossible, since the exponent, and therefore the initial mass of the rocket, increase without limit. This extreme case is also readily explained; if the thrust of the engine is just equal to the force of gravity the rocket will hang in the air in equilibrium and after combustion of its propellant will descend to the very stand from which it was launched.

This is a cardinal distinction between the launching of a rocket in gravity-free space and launching in actual conditions. In the first case the velocity attained depends only on the ratio between the fuel consumed and the weight of the rocket and on the caloricity of the fuel. The rapidity of the fuel combustion makes no difference. It is important only that the direction of the thrust and that of the actual velocity coincide; in other words, in gravity-free space the velocity attained is wholly determined by the propellant carried,, and no flight "strategy" (aside from the most primitive, which consists of not using the engine to slow the rocket down) can change the situation. In this case success is determined purely by

power: the more fuel taken, the higher the velocity obtained. In the presence of gravity, however, as the last formula shows, everything is far from being governed by the mass ratio of the rocket; the method of fuel consumption is also important. In other words, here power does not wholly determine the success of a launching; the same quantity of fuel can give better results if the flight is intelligently planned, than if it is badly planned.

It was quite clear to Kondratyuk from the very beginning that deduction of the formal ratio for a rocket in empty space was minor compared to calculation of its trajectory and flight strategy. He was readily convinced of this by the example of a "suspended" rocket expending all its fuel to no purpose, which he adduced in his manuscript. From this point he went on to devote many pages to "means of escape" and to determination of the most efficient of them. It turned out that the efficiency of the engine depended not only upon the magnitude of the acceleration, i.e., the intensity of the fuel combustion, but also upon the direction of the boost at launching. Kondratyuk discovered this in comparing "radial escape," which he was discussing, with "tangential escape," which he termed "method number two."

b) The rocket is boosted circumferentially. In this case the engine thrust, which is equal to k times the weight of the rocket, must be applied at such an angle to the horizon that the resultant* of thrust and weight be directed along the horizontal. The actual acceleration will then be equal to $g\sqrt{k^2-1}$ and the formula for the weight of the rocket will therefore have the form

$$m_{\text{init.}} = m_{\text{fin}} e^{\frac{v}{\sqrt{2p}} \frac{k}{\sqrt{k^2-1}}}.$$

If the first and second means of boost are compared, it is evident that in the case of horizontal flight the exponent contains the expression $\frac{k}{k-1}$, while for vertical flight this is replaced by $\frac{k}{\sqrt{k^2-1}}$. The first factor is greater than the second, as can be seen by writing them respectively in the forms

$$\frac{k}{\sqrt{(k-1)(k-1)}},$$

and

$$\frac{k}{\sqrt{(k-1)(k+1)}}.$$

From this follows the fundamental conclusion that for acceleration to the same velocity and for the same engine rating (identical k), flight along the horizontal requires less fuel than vertical flight.

Kondratyuk immediately pointed out that this calculation is only very approximate. The inaccuracy of the reasoning was neglected in both cases. In calculating vertical flight he did not take into account the reduction in the force of gravity as one gets farther from the surface of the earth, as a result of which the actual acceleration would be not $\frac{gk}{k-1}$, but greater. In the case of horizontal boost, or, more correctly, circumferential boost, centrifugal force begins to act as the speed of the rocket increases, and as a result the rocket becomes "lighter" and the actual acceleration equals $g\sqrt{k^2-1}$.

* [The Russian text has "component," but this seems to be in error.]

In both cases the true situation will be more favorable than appears from the approximate formulas obtained. The question arises whether some rectification of the conditions considered might not be made sufficiently great and sufficiently different in the two cases, as to alter the balance in favor of vertical boosting.

Kondratyuk gives no precise conclusion in his manuscript, but remarks only that the superiority of the second method is evident for a judicious choice of k, such as $k = 5$, even if the additional gains resulting from centrifugal force are neglected.

Statement of the means of flight from the earth is fundamental in Kondratyuk's paper, since it is the starting point of every theory of the geometry of flight. Study of this subject led him to the discovery of the most efficient "flight curve," which was depicted on the cover of his book, published in 1929: a circle developing into ever more stretched ellipses with foci at the center of the earth and perigee at one and the same altitude. The determination of the most efficient trajectories and engine ratings, together with the theory of multistage rockets and the theory, brilliant both in plan and development, of intermediate bases, was the branch of astronautics in which Kondratyuk's talents were most clearly apparent. This theory is complicated and in the manuscript of 1919 Kondratyuk did not lay out all of its elements with full mathematical rigor, but the full command of his rare intuition and his rough calculations, which are not presented in the paper, kept his conclusions free of error.

How important is the theory of flight trajectories which Kondratyuk so carefully reasoned out? In the launching of one, two, or a number of the first space rockets the question of fuel conservation was not too important, for the realization of the project as a whole, design and construction of body, engine, guidance system, etc., was enormously costly. The idea of multistage rockets theoretically resolved the question of launching as many heavy bodies as desired into space by increasing the number of stages and their dimensions. This increase is not reflected in any great rise in the cost of the whole complicated series of steps involved in the building of a rocket, and it might therefore seem, if one has in mind the unchanging scientific value of the information gained from space rockets, that there is no special reason for the careful calculation of trajectories and engine ratings, and at the same time, for the excessive complication of the guiding system, merely in order to save some fuel.

However, let us imagine the day (which as everyone realizes is not far off) when space flight will no longer be an exceptional occurrence, but a normal thing, a branch of transport engineering. People will travel to other planets, and from the latter to the earth there will be a flow, at first of samples, and afterwards, perhaps, of industrially significant minerals. Every year hundreds of perfected spaceships will set out to different corners of the solar system in accord with a plan to master the cosmos. Considerations of profitableness and economy will then be of great importance. The development of a guidance system will permit adoption of any flight scheme desired and it will then be necessary to formulate the scheme in such a way that the rocket be as little bulky as possible, have the smallest possible number of stages, and that as great a part of its volume as possible be occupied by payload. Spaceships will then depart and return on an optimum trajectory.

It is interesting to note that Tsiolkovskii, Kondratyuk, and Tsander all started from the conscious wish to realize manned space flight, and came to the conclusion that it could be done only by means of rockets, whereupon they derived the fundamental formulas of rocket flight. Bearing in mind that the final goal was the journey of a human crew to other planets and its return to the earth, Kondratyuk could not fail to be concerned that the magnitude of the expression giving the initial weight of the rocket in the stage exponent be as small as possible. This concern arose immediately after deduction of the fundamental formula and it testifies to Kondratyuk's practical approach to the problem and his engineering viewpoint, which also characterize his other work.

Kondratyuk's idea about the most efficient trajectories is extraordinarily beautiful, but in the 1919 manuscript it is presented in exceptionally concise form. It is therefore worthwhile to examine it in more detail and to touch upon the physical considerations which Kondratyuk regarded as evident, and which were at the basis of the conclusion that departing flight along the horizontal is more efficient. For this purpose a quantity which will be termed the efficiency factor of a rocket engine is here introduced. The "efficiency factor" is the ratio of "useful work" to "work done", i.e., the ratio of the increase of the kinetic energy of the rocket to the energy of the explosion.

Where does the energy p liberated by the explosion of a unit of mass go to? First, it contributes to a change in the kinetic energy of the rocket, and second, to a change in the kinetic energy of the mass of gas ejected from the nozzle. This gas previously moved in the tanks of the rocket with velocity v, and now flies out of the rocket with velocity $v - V$. The system of rocket and gases is a closed system, to which the law of the conservation of energy may be applied. If the change in the energy of the whole system is computed, it is found to be exactly equal to the energy of the explosion. The rocket body is only a part of the system, and the law of the conservation of energy can therefore not be applied to it alone, leaving the other part out of consideration. The efficiency factor should therefore strictly speaking not be so named, but the term will be retained, bearing in mind its arbitrariness, since the ratio of the increase of the kinetic energy of the rocket to the energy of the explosion is characteristic of the efficiency of fuel consumption. We shall now consider why this quantity can be greater than unity.

Let the rocket have a velocity equal to half of the exhaust velocity. The portion of the gases ready for combustion moves in the storage tanks also with a velocity $v = V/2$. The explosion then takes place and the gases are ejected with a velocity V relative to the rocket, but since the rocket is flying forward with velocity v (neglecting the very small change in the speed of the rocket after ejection of a small part of the gases), the gases fly into space with a velocity again $V/2$, but in the opposite direction from the rocket, and no longer in its tanks, but independently. The kinetic energy, however, does not depend on the direction of the velocity, but only on its magnitude, and the kinetic energy of the gases is therefore unchanged after the explosion. If only the gases are regarded, they have merely changed direction, now flying backwards, instead of forwards, with velocity $V/2$. Since, however, the gases have not changed their kinetic energy, it is clear that all of the energy of the explosion has gone to increase the kinetic energy of the rocket, i.e., that the efficiency factor is equal to unity.

If the rocket were moving with a velocity greater than half the exhaust velocity, and for instance greatly exceeded that velocity, the result would be as follows. Until the explosion the gases would have been moving in the tanks with enormous velocity. After combustion they would fly backwards with a velocity V relative to the rocket, and consequently, would move behind the rocket with a velocity less than before. From this it follows that the increase in the kinetic velocity of the rocket itself would consist of the energy of the explosion plus the kinetic energy lost by the gases. In other words, if the rocket is moving with great velocity, kinetic energy can be taken from the fuel previously accelerated together with the rocket in its tanks. In this sense it is true to say that the energy expended to accelerate the fuel in the tanks during the boost phase of the rocket is not lost to no purpose; it can subsequently be recovered, and the velocity acquired by the fuel can advantageously be used.

These considerations in many cases resolve the question of the most efficient method of flight. In the case of vertical ascent energy is expended to overcome gravity and velocity increases slowly. In other words, energy is spent (other than to communicate potential and kinetic energy to the rocket itself) to carry the fuel aloft, i.e., it is transformed into the potential energy of the mass of fuel carried to a great altitude. This energy, however, cannot subsequently be used and is rightly called "dead." If, however, the initial boost is along the horizontal, or more correctly, along the circumference, passing above the earth at one and the same altitude, the energy will not be expended to raise the fuel, but only to accelerate it, i.e., it will be transformed into the kinetic energy of the fuel, which can subsequently be used.

As is known from the theory of gravity, when any body travels away from the earth's surface towards infinity (i.e., to such a great distance that the force of the earth's gravity is no longer felt), it must receive a definite energy, i.e., a rocket flying into space must receive a strictly determined amount of energy. Unfortunately, however, far greater quantities of energy must actually be expended since it must also be imparted to the fuel. If the second flight method is used, however, the energy communicated to the fuel will be less, since it will take the form of kinetic energy, which is partially recoverable. In the first case this parasitic expenditure of energy will be greater, and consequently, assuming the same engine rating, the energy communicated to the rocket will be less.

The fraction of the kinetic energy of the gases that returns to the rocket, that is, the magnitude of the energy transferred from the "useless" to the "useful" part of the system, will be greater, the greater the velocity of the rocket. This means that on a given section of the trajectory the rocket engine will operate more efficiently, the higher the velocity. This is also apparent from the following reasoning: the work done by the rocket in a unit of time is equal to the product of the thrust (which is dependent upon the intensity of the fuel combustion and the caloricity of the fuel) and the distance traveled by the rocket in a unit of time. This last, however, is numerically equal to the velocity. The power going to boost the rocket, i.e., the useful power, is equal to the product of the thrust and the velocity of the rocket. For very great velocities the useful power can be immeasurably greater than the power derived from the fuel burned. These velocities make possible a considerably greater increase in energy than the chemical energy stored in the rocket fuel. As appears from the above

reasoning, this does not violate the law of conservation of energy; it is simply that the energy at some point applied to accelerate the fuel to very great velocity begins "unexpectedly" to return. Since the efficiency factor is directly proportional to the velocity, it is clearly advantageous to start the engine on those parts of the trajectory where the velocity is greatest. Now suppose the rocket already to have been accelerated to a velocity somewhat above the circular velocity, and to be orbiting the earth along an ellipse. The problem now takes the form of further acceleration of the rocket and transformation of the elliptical orbit into a parabola. It is well known, however, that a body in elliptical orbit in the gravity field of the earth has its maximum velocity at perigee, that is, at the point of its closest approach to the focus of the ellipse (where the center of the attracting body, in this case the earth, is located). It is therefore best to start the engine at perigee. The gravity field must be allowed to accelerate the spaceship, and the engines must be engaged when rushing past with very great velocity at a minimum distance from the surface of the earth. The engines will then operate at maximum efficiency. After the jet engines have been running for a short time, the velocity of the rocket will increase, and the next ellipse described by the rocket will be greater than the first: that is, its apogee (the point farthest from the focus) will be farther away. When the perigee of this enlarged ellipse is reached, i.e., after one revolution, the engines are again started. Repetition of this process several times removes the apogee off towards infinity, bringing the rocket out into space along a parabolic orbit. This flight program – circumferential boost followed by transformation of the trajectory into an elliptical orbit and successive traversal of a family of ellipses steadily widening out into a parabola, with engines started at perigee – is theoretically the most efficient for the case under consideration.

Development of the ideas related to the most efficient flight program has very great significance for the future. Perhaps attainment of the most distant heavenly bodies will turn out to be no more complicated than the launching of artificial earth satellites, if a flight program is carefully worked out using intermediate planets and artificial bases. Another remarkable Soviet scientist, Tsander, working in rocketry, pointed out, with reference to trajectories, that if some other heavenly body, such as the moon, is found along the route to another planet, such as Mars, it is advantageous to plan the trajectory of the flight to Mars in such a way as to pass close to the moon. In the case of flight past the moon the velocity of the vehicle will be greatly increased and the engine, if it is started at this moment, will operate at very high efficiency. In other words, if the vehicle is drawn as close as possible to the moon, it will seem to be falling towards its surface. The moon will then begin to communicate to the rocket, and therefore to the fuel in its tanks, considerable velocity. The potential energy of the "dead stock" of fuel will be transformed into a form suitable for subsequent combustion and conversion into kinetic energy. When it flies past the point of closest approach to the moon, the rocket begins to extract this energy from the fuel as a supplement to the thermal energy of combustion. By this means the journey to Mars will bring to mind a spring from an intermediate trampoline and will be accomplished with less consumption of fuel than in the case of straight flight. Tsander proposed to use all solid intermediate celestial bodies in this way for flights to distant

planets. The exploitation of big planets such as Jupiter and Saturn as intermediate centers of attraction would be especially advantageous; for example, the combustion of one gram of fuel near the surface of Jupiter would be equivalent to the combustion of almost six grams near the earth.

Kondratyuk's proposal to accelerate rockets along a family of ellipses is actually identical to Tsander's idea of exploiting intermediate planets with the sole difference that in the former case, the Earth itself, to which the rocket returns several times in the course of flight, is the "trampoline."

Kondratyuk's original researches on maximum efficiency flight made a fundamental theoretical contribution to the human conquest of space, and his results underline its actuality. In the very first page of his manuscript Kondratyuk estimated the ratio of the initial mass of the rocket with fuel to the mass of the rocket returning to Earth, obtaining 55 for a rocket running on detonating gas. This figure receives an exclamation point and is followed by the sentence: "Ratio 55... is not so bad; the rocket is quite feasible!!!!"*

This ratio is in fact close to what is actually possible, and can be further reduced by the method developed by Kondratyuk. This can be done by three methods which receive detailed analysis in the manuscript: (1) loading on board the rocket several tanks of fuel which are jettisoned after being emptied; (2) a system of intermediate bases in space; (3) velocity damping upon return by braking in air. Kondratyuk thus concluded that actual rocket designs could reach circular velocity, after which, by the theory of efficient trajectories or one of the three principles mentioned above, an insignificant increase in the quantity of fuel would make it possible to get to remote planets. The results of his preliminary calculations inspired Kondratyuk to careful consideration of the details, to which the following pages of the manuscript are devoted.

Kondratyuk nowhere discusses the possibility of interstellar flight in detail, justifiably so, since the enormous distances of the stars make such projects seem fantastic even at present. Kondratyuk tried in every way to keep his book free of fantasy.

DISCUSSION OF OTHER POSSIBLE SYSTEMS

Trying to persuade his readers that his method is the only correct one, Kondratyuk diverts two pages to a discussion of what machines beyond thermochemical rockets are deserving of attention. First he considers a scheme in which a steel wire, unrolling from a rotating spool on board the space vehicle, is ejected together with the gases. The wire would then be flying in one direction and the spool in the other. This scheme, as Kondratyuk's letter to Rynin testifies, was one of the earliest. In the manuscript Kondratyuk made a calculation and found that the design with the wire would require a ratio of initial to final mass equal to 10^{17}! This project clearly was totally impracticable.

The second idea chosen by Kondratyuk is extraordinarily interesting. It involves exploiting the recoil of charged particles, cathode rays, as Kondratyuk calls them, accelerated by an electric field. As the author

* Manuscript, p. 13.

shows, they can have very high velocities, almost equal to the velocity of light. This implies that ejection of a unit of mass in this way would give rise to an immeasurably greater thrust than in a thermochemical rocket. The disadvantage of this method, according to Kondratyuk, is in the enormous quantity of energy required to accelerate an appreciable mass to a velocity approaching that of light. Its second shortcoming is that in ejecting charged particles the rocket begins to acquire a charge opposite to that of the particles.

Kondratyuk suggested the following means of overcoming these deficiencies. First, it was necessary to ponder the exploitation of solar energy by means of mirrors exposed by the rocket during flight in interplanetary space (these mirrors will be discussed in more detail later). If solar energy could be trapped and converted into electrical energy, it could be used to accelerate the charged atomic particles on board the rocket. Second, in order to avoid carrying a charge off into space the accelerated particles could be passed through a metallic layer in which they would lose their charge. The heating of this layer, if desired, could be used towards meeting the needs of the rocket.

It is worthy of note that Kondratyuk's last idea has been realized, with reference not to rockets, but to charged particle accelerators. Most recently so-called "charge-transfer accelerators" have been built, in which the accelerated ion passes through a metallic foil and changes its charge. Without performing experiments Kondratyuk could not arrive at a final conclusion about the practical feasibility of the method, but the path he indicated was entirely correct.

Kondratyuk concluded his consideration of the rocket design with ejection of electrically accelerated atomic particles with the following words: "Although at present it is hard for me to imagine a jet machine founded on material radiation... it is worthwhile to think about it and work on it; success would assure a velocity so enormous that it could not be attained by even the largest rocket. It might even become possible to verify the Theory of Relativity."*

The last sentence means that if a rocket moving with a velocity close to that of light could be built, its crew would actually feel in themselves the change of time scale which occurs, according to the Theory of Relativity, with motion at great velocities; i.e., upon their return to the Earth from space, they would find that the time elapsed on board the rocket was different from that on earth.

Kondratyuk limited himself to the consideration of thermochemical rockets, as the most realistic machines of the near future. Having made this choice, he applied himself to the design of projectile shapes, distribution of their separate parts, and design of the different components.

GENERAL SHAPE OF PROJECTILES

Kondratyuk devoted a great deal of attention to the engineering side of rocket design. This resulted not only from his own special talents (Kondratyuk is known to have been an exceptional mechanic with the "golden

* Manuscript, p. 32.

hand" of a master craftsman), but also from the fact that the book, from its very beginning, was conceived as a concrete, practical study, almost as the outline of a project.

With his first words Kondratyuk concluded that a rocket should have not just one, but a number of vessels for fuel. This was necessary because "a single vessel would have a considerable weight and towards the end of the flight, after combustion of nearly all the propellant, would constitute a totally superfluous mass which might increase the mass of the projectile several-fold and require a large quantity of propellant [for its acceleration]; it might even make the whole undertaking impossible."* Further, ". . . several vessels of varying size are needed. The propellant is taken first from the larger ones which after they have been emptied, are simply jettisoned, while the next containers are broached. The dimensions of the vessels must be so calculated as to make the weight of the vessel being emptied (vessel alone without propellant) at any moment constitute one and the same fraction of the weight of the entire remaining rocket, for all the vessels. This fraction must be worked out bearing in mind, first, that it be as small as possible; and second, that the number of vessels not be so great as to make construction of the projectile excessively complicated."**

Kondratyuk had to study many special problems connected with the construction of a space vehicle, such as distribution and shape of the tanks, construction of pipes and guidance systems, etc. He displayed great competence and engineering intuition in solving these problems. For example, he developed an interesting theory to settle the question of how to make vessels for fuel as light as possible for a given capacity, in view of the considerable g-loads resulting from acceleration. His proposal for the control of rockets is also of interest. The very tip of the vent pipe or nozzle was made movable, or else attached to the end of the exhaust orifice on a universal joint was a short piece of pipe of limited mobility, which could be guided by a system of thrusts described in detail in Kondratyuk's manuscript. A slight turn of the movable piece of pipe diverts the gas stream, and the rocket begins to turn in space. The idea brings to mind that proposed by Tsiolkovskii in 1903.

Kondratyuk also devoted considerable attention to the problem of permanent orientation in airless space, to achieve which, in his opinion, a gyroscope was needed. He devoted three pages of his manuscript to the development of his design, which he termed a "biaxial astatic gyroscope." After this, four pages (which is a good deal, considering the compactness of the whole manuscript) are devoted to combustion chamber design and propellant combustion methods. According to Kondratyuk, the chamber should be so constructed that when necessary it could be isolated both from the feed pipes connecting it with the propellant tanks and from external space. He considered the possibility of simultaneously fulfilling the requirements that the cabin be hermetically closed off from the chamber, and that the chamber be controlled. Both electrical and mechanical methods for the transmission of control signals were proposed. Kondratyuk also planned to surround the chamber with fuel tanks, which would improve chamber cooling and result in higher energy from combustion of the propellant because of its preliminary heating.

* Manuscript, pp. 34-35.

** Ibid., pp. 35-36.

Kondratyuk also subjected methods of propellant ignition to detailed analysis, suggesting two schemes. In the first, the gases (oxygen and hydrogen) are pre-mixed and constitute a detonating gas upon entry into the chamber; in the second, mixing takes place directly in the chamber itself. He provided designs for the chamber and fuel feed mechanism with illustrative sketches in both cases. In the first case the possibility of fire in the feed pipe was precluded by a metal grid, like that of a Davy lamp, separating the pipe from the chamber.

Another four pages are devoted to the description of heating systems, pumps, and regulators, followed by designs for pipes and other parts. A separate paragraph is given to a mechanical accelerometer constituting part of the fuel feed control system. Kondratyuk also considers the possibility of constructing a liquid accelerometer to measure acceleration by the speed with which a liquid flows from one vessel to another through a narrow pipe. In this case observations are facilitated by the fact that the total flow is proportional to the amount of propellant burned.

It goes without saying that for all his engineering talent, Kondratyuk, sitting at a desk with pencil and paper, could not foresee the innumerable difficulties and complications that we now know to arise in the realization of space flight. Kondratyuk himself felt this distinctly, and his designs for various components are intended more to convince the reader of the fundamental feasibility of manufacturing all of the rocket parts and of their combined functioning than to present a final conclusion. In almost every case where he describes the design of rocket components Kondratyuk considers two or three different variations and never shows a preference among them, as if by so doing to underline the necessity of further research. He considered experiment the most important aspect of future study, however, and remarked more than once that without experimentation no more advances could be made in the development of the theory of space vehicles. He had no doubt that however carefully a scientist constructed the theory of a projectile, detailed experimental study of every part would yield unexpected results that might demonstrate the unfeasibility of the design or reveal the possibility of creating a better one. In his letter to Professor Rynin Kondratyuk wrote: "The idea of space flight. . . possessed me for a long time, during which I repeatedly returned to it, almost reaching the limit beyond which further fruitful work is impossible without parallel experimentation."*

Taking this into account, the technical details of Kondratyuk's spaceship design are not given here. Despite their interest, they were probably not the only possible, and in many cases, not the best designs, and their interest for us is certainly less than that of the extraordinary work on trajectories presented at the beginning of the essay. The chapter on the complication of flight by atmospheric conditions, which follows that on rocket design in the manuscript, is also of much greater interest.

COMPLICATIONS INTRODUCED BY THE ATMOSPHERE

Upon first impression, the presence of the atmosphere appears to have a harmful effect, first, because a rocket flying through the atmosphere will

* Rynin, N.A. "Teoriya kosmicheskogo poleta" (Theory of Space Flight), p.343. Leningrad. 1932.

experience friction, and second, because "... atmospheric pressure increases the pressure and density of the gases at the exhaust orifice, making it more difficult for them to stream away, and thereby leads to a reduction in their exhaust velocity and a reduction in efficiency."*

To overcome the second of these effects Kondratyuk suggested using a special adapter to make the exhaust orifice narrower during flight through the atmosphere. The elasticity of the gases at the orifice would then be increased and the atmospheric pressure encountered would not have such a great effect. Kondratyuk proposed using atmospheric pressure to avoid special expenditure of energy for further compression of the propellant, which is required if the pipe is narrowed. The essence of his idea was that since atmospheric pressure acts not only upon the exhaust aperture, but also upon the tanks of propellant, use could be made of it to ensure that the energy for displacement of the gases into the chamber were the same as in a vacuum.

For the greatest possible reduction of the first undesirable effect, Kondratyuk proposed developing the most streamlined missile shape (which, however, could not be determined until appropriate experiments had been performed), and giving the projectile a polished outer surface. He devoted a special study to detailed exposition of the problems of body heating during high-velocity movement through air: "Temperatura dvizhushchegosya gaza otnositel'no nepodvizhnogo tela" (Temperature of a Moving Gas Relative to an Immobile Body).

But all of these measures, in Kondratyuk's opinion, could not totally eliminate the heating effect of the rocket in air, and the consequent great reduction in velocity. Bearing in mind that the total extent of the dense layer of the atmosphere is only a few dozen kilometers, it would be necessary to consider "first" and "second" means of take-off for space flight: the first kilometers would be traversed in vertical flight, but the rocket would then be turned into a course parallel to the surface of the earth for further acceleration by the "second" method. (It should be recalled that the rockets already launched into space have followed exactly this type of scheme, combining vertical and horizontal boost.) The first kilometers must be traversed vertically not because this is more efficient from the point of view of trajectory theory, but in order to pass through the dense layers as quickly as possible. Leaving the moon, for example, take-off flight would have to be along the horizontal from the very beginning, and boost applied so as to give a trajectory passing over the surface of the moon always at the same altitude (naturally, selected so as to eliminate the danger of collision with cliffs).

It is clearly unfortunate that presence of the atmosphere precludes take-off flight along the theoretically most efficient trajectory. The researcher cannot rest when confronted with a manifest obstacle, however, and must find a means of using the atmosphere to serve his purpose.

The atmosphere can certainly be utilized during return to the earth, when its upper layers can be used to brake the rocket without fuel expenditure to reduce its excessive velocity. If it were possible to develop a design in which all the excess velocity could be eliminated by the atmosphere, it would be converted from the enemy of astronauts to their

* Manuscript, p. 80.

ally, since they would have to take fuel aboard only for the ascending leg. This useful effect would more than compensate for the harmful effect of directing the initial boost phase along the vertical and of frictional losses.

After presenting these considerations, Kondratyuk turns to concrete analysis. First, it is clear that reduction of velocity must take place high above the earth where the air density is insignificant, since the rocket would burn up from friction in the denser layers of the atmophere. Kondratyuk noted that in this case guided landing would be extraordinarily complicated: "This guidance must consist of remaining as long as possible, i. e., until almost all velocity has been lost, in the upper layers of the atmosphere and descending to the denser layers only with reduced speed... This requires extraordinarily delicate control.

"If there is the least inaccuracy in the angle of attack, the projectile will hurl itself into the dense layers of the atmosphere, where it will not withstand the resistance and the passengers will not withstand the deceleration, or it will simply strike the earth. Otherwise it might fly upward out of the atmosphere into space, to fall later to the earth at an angle which would make catastrophe inevitable. Of course for velocities measured in tens of kilometers per second the atmospheric layer is not thick enough to sustain rotation."*

Kondratyuk proposed connecting the elevators with a gyroscope located inside the rocket as a means of turning the rudder as needed. He could not give concrete designs for such a guidance system at that time, since a theory of automatic control in the modern sense of the words did not then exist. Now, thanks to the latest achievements in cybernetics and automation, the problem of rudder guidance of rockets during velocity reduction in the upper layers of the atmosphere is no longer insuperable. There is no doubt that Kondratyuk's scheme for utilization of the atmosphere, which he worked out independently of Tsander and Tsiolkovskii, who also expressed this idea, will be realized in future spaceships.

Kondratyuk considered various means of reducing heating effects — liquid cooling, construction of the surface of the projectile in the form of several consecutively shed skins, and exchange (in case of damage) of the sharp pointed nose. He suggested making the surface of the rocket out of the material which was most refractory and at the same time could be most highly polished — quartz, for example. He spent some time discussing means of achieving thermal isolation, suggesting adoption of approximately the same method as that used in Dewar vessels.

Kondratyuk emphasized the importance of careful experimentation on air friction and cooling systems as follows: "In general, this seems to me quite a difficult problem. Many experiments, gradually mounting to a velocity of 22 km/sec (for the second means, and 35 km/sec for the third) will have to be made. If burnup can be avoided for the lowest velocities, which will still be considerable, landing by a combination of methods will be possible: some velocity can be lost outside the atmosphere, and only part of it left to be dealt with by atmospheric braking."**

Although he recognized the complexity of the problem and the impossibility of making accurate deductions without persistent and difficult experimentation, Kondratyuk evidently regarded the possibility of utilizing

* Manuscript, pp. 96-98.

** Manuscript, pp. 100-100 obverse.

the atmosphere quite optimistically. However, in his eagerness to achieve space flight with minimum fuel consumption, he also thought about what might be employed in airless space.

MIRRORS

Kondratyuk begins with a theory of mirrors reflecting solar light in such a way that it is collected either at one point or on a single line. Depending on whether the first or second of these methods is used, the mirror has the form of either a paraboloid of revolution or a parabolic cylinder. The design of the mirrors is given a very detailed analysis, occupying a total of seven pages with the addition of several sketches, which indicates that the author attached great importance to the utilization of solar energy in outer space. The theory of such mirrors, however, presents nothing original, but had been known for a long time before Kondratyuk and can therefore be passed over in this paper. What is of interest is the use that Kondratyuk proposed to make of solar energy obtained by means of mirrors.

First of all, concentrated solar light could be passed through water to separate it into hydrogen and oxygen. In this case the fuel, or detonating gas, could be brought from earth in the most compact form, as water. The design of the storage tanks would be correspondingly simplified and their weight considerably reduced.

Besides this, the solar heat collected by the mirrors could be used for the purely internal needs of the rocket – heating, instruments, etc. Approximate calculations brought Kondratyuk to the conclusion that the mirrors had to have quite a considerable area, but that they were feasible.

In practice the mirrors unfolded in fully assembled form and rotated only in outer space, where the rocket moved by inertia and did not experience any g-loads. In other words, all of the objects aboard the rocket fly independently of it along the same trajectory and consequently no forces originate among the separate parts of the system; gravity is absent. For this reason, however thin the surface of the mirror, it will not cave in under its own gravity, even if its area amounts to hundreds of square meters. Kondratyuk discusses the set-up of his folding mirror in as much detail as he devotes to the description of the arrangement for the decomposition of water. He gives special attention to the cylindrical mirror and gives the design of the rotating frame and the metallic reflecting foil stretched upon it.

His thoughts on mirrors for the collection of solar light, and also his reflections on the fact that such mirrors could be built only in the absence of gravity (otherwise the sides of the mirrors would have to be made thick and the quantity of material used would be far greater than the solar energy collected), led Kondratyuk to the proposal which is one of the finest ideas in his manuscript. He proposed using rockets to create a belt of metallic reflecting foils, flying in circular orbits around the earth. The negligible thickness of the foil would make it possible for comparatively small rockets to put out into orbit a number of foils whose collective surface area would be enormous. Solar rays, reflected from this foil, would then fall upon

the earth from distant regions of space. One might say that the earth would receive a greater quantity of solar energy than it presently receives. Such "distribution of the earth's collecting facilities," in Kondratyuk's opinion, could be used in future for energetic purposes, and to change the climate of the earth's cold regions.

Not long ago an engineer who of course knew nothing of Kondratyuk's mirror theory developed a project for the creation of a dust belt around the earth for exactly the purposes meant to be served by Kondratyuk's orbiting mirrors. It must be admitted that Kondratyuk's proposal is much better, since minute dust particles or molecules would be subjected to the influence of cosmic rays and ultraviolet solar radiation, would become ionized, and under the action of the earth's magnetic field would migrate to an equatorial orbit, where instead of collecting solar energy from a wide extra-terrestrial region, they would obscure the light of the sun.

The last chapter in the manuscript, and one of the most interesting, is on the theory of flight with the use of intermediate bases. It occupies the last ten pages and completes the study of all possible means to facilitate travel to other planets and back, to make it actual and worth the effort that must be expended.

FLIGHT THEORY

Kondratyuk calculated the quantities of propellant required for travel from the earth to another planet and back. In so doing he considered the fact that the enormous velocity of the spaceship must be reduced in landing on the planet. In order to attain this velocity again at take-off, great fuel consumption would be necessary, and it would therefore be convenient to have an intermediate base in the form of an artificial earth satellite. Rockets would deliver fuel from the earth to the base and the interplanetary expedition could then take it on board while moored at the base. Kondratyuk thought it better to make the base a satellite of the moon, rather than the earth (in the opinion of Professor Vetchinkin, this was one of his major discoveries). After developing his base theory, Kondratyuk concluded that with their help, and correct use of the laws of gravity, i. e., once skill in drawing up a flight plan had been attained, it would be possible to conquer all of the space about the sun soon after the first attainment of circular velocity. "Bases could, in general, give incomparably great freedom of action," he wrote.*

With reference to the shipment of propellant to intermediate bases, Kondratyuk speaks so graphically and with such conviction of sending an interplanetary transport train, that it is hard to restrain oneself from reproducing the entire passage:

"... it is best to send the propellant transport not by a single projectile, but by quite a few, or even many, interconnected by a quartz cable, like a burst of machine-gun fire. The cable must have some slack which can be extended only with some effort, but does not spring back. Each projectile must have in its nose an instrument which automatically turns it in the direction of strongest illumination. The transport must be launched at

* Manuscript, p. 128.

sunrise at an angle to the east, so that after leaving the atmosphere, the projectile will automatically turn towards the sun, i.e., its axis will be parallel to the surface of the earth (for ascent) and after attaining (as a rocket) sufficient velocity in this direction, it will behave like a satellite. Some of the projectiles will contain propellant, and others, the smaller part, will carry signals visible from far off. Besides large surfaces or spheres of paper or silk, the signals might be in the form of a large electric bulb or a powerful lamp (of special construction, which would withstand the acceleration upon firing), which would obtain energy from the sun by means of mirrors."*

Since the propellant transport did not carry people, it was not so sensitive to the g-loads resulting from acceleration, and Kondratyuk therefore proposed using a big cannon to launch it, so that it would receive considerable velocity. Further velocity would be obtained by means of a jet engine installed in the transport. This scheme brought Kondratyuk back to the idea of an electric cannon.

To sum up, Kondratyuk's ideas on the use of the gravity of the planets, solar energy, intermediate bases, and atmospheric resistance are enough to convince us of the feasibility of the most daring space flights.

This remarkable paper, written at the period of the revolution and beginning of the civil war, concludes with the exclamation, "Then, if it were possible to fly there by means of a cannon, and return by means of the atmosphere, by taking on board the projectile a not even especially great quantity of propellant, what monograms might we not describe in the universe! "**

Kondratyuk's words turned out to be prophetic. When he said, "It is quite possible that we shall in the near future begin to be true lords of our planet and we must therefore see enormous significance in the conquest of the solar system,"† he was sincerely convinced that the completion of this task did not lie beyond the creative powers of his people.

The conquest of the cosmos has begun. It is proceeding along the path marked out by three remarkable pioneers of space science and engineering — Tsiolkovskii, Tsander, and Kondratyuk.

* Ibid., pp. 130 obverse to 132 obverse.

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† Ibid.

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120. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov. Glava VII. Naibol'shaya skorost' vrashcheniya tel i zapas ikh mekhanicheskoi energii (Idem., Chapter VII. Maximum Rotational Velocity of Bodies and Their Store of Mechanical Energy), entry 1, file 104. Fragments of a paper, autograph and typewritten copy with author's corrections, 1934-1935.

121. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov. Glava X. Naibol'shaya skorost' rakety (Idem., Chapter X. Maximum Rocket Velocity), entry 1, file 105. Autograph and typewritten copy with author's corrections. 28 January, 1935.

122. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov. Glava IV. Soprotivlenie gazovoi sredy dvizheniyu plavnykh ptitsepodobnykh tel (Idem., Chapter IV. Resistance Offered by a Gaseous Medium to the Motion of Floating Birdlike Bodies), entry 1, file 107. Autograph and typescript with author's corrections. 12 March — 10 August, 1935.

123. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov. Glava VI. Energiya khimicheskogo soedineniya veshchestv i vybor sostavnykh chastei vzryva (Idem., Chapter VI. Energy of the Chemical Combination of Substances and Choice of the Components of the Explosion), entry 1, file 108. Autograph and typescript with author's corrections, 21 March, 1935.

124. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov, Glava XI. Grubyi raschet poleta raketoplana (Idem., Chapter XI. Rough Flight Calculation for a Rocket-Propelled Airplane), entry 1, file 109. Typescript with author's corrections, 21 March, 1935.

125. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov, Glava VIII-IX (Idem., Chapters VIII-IX), entry 1, file 111. Outlines relating to engine construction. Autograph. 14 October 1934 — 12 August, 1935.

126. Novye dvigateli dvukh tipov (Two Types of New Engines), entry 1, file 112. Article based on Chapter VIII of "Osnovy postroeniya..." Typescript with author's corrections. 29 March, 1935.

127. Vtoroi tip motorov — s zapasnym kislorodnym soedineniem i bez vody (Engines of the Second Type, Using a Reserve Oxygen Compound and No Water), entry 1, file 113. Article based on Chapter IX of "Osnovy postroeniya..." Typescript, 17 April, 1935.

128. Osnovy postroeniya gazovykh mashin, motorov i letatel'nykh priborov, Glava V. Plotnost', temperatura i davlenie raznykh sloev atmosfery (Fundamentals of the Construction of Gas Machines, Motors, and Flying Machines, Chapter V, Density, Temperature, and Pressure of Various Atmospheric Layers), entry 1, file 117, Autograph and typescript with author's corrections. 1935.

129. Primenenie reaktivnykh priborov k issledovaniyu stratosfery (Application of Jet Machines to Stratospheric Research), entry 1, file 106. Unfinished article. Autograph and typescript, 27 February, 1935.

130. Voobshche o dvigatelyakh, prigodnykh k poletam (General Remarks about Engines Suitable for Flight), entry 1, file 110. Article, typescript, with author's corrections, 25 March, 1935.

131. Osobyi priem dostizheniya vysshikh skorostei reaktivnymi letatel'nymi mashinami (Special Method for the Attainment of Maximum Velocities by Jet Aircraft), entry 1, file 114. Article, autograph and typescript with author's corrections, 23 April, 1935.

132. Izobretatelyam reaktivnykh mashin (To the Inventors of Jet Machines), entry 1, file 115. Article, autograph and typescript, 28 April, 1935.

133. Fantaziya li zaatmosfernye polety? (Is Flight Outside the Atmosphere a Fantasy?), entry 1, file 116. Article, autograph and typescript with author's corrections, 28 July, 1935. Published in the newspaper "Komsomol'skaya Pravda," 18 September, 1935 (see item 143).

134. Aviatsiya, vozdukhoplavanie i raketoplavanie v 20-m veke (Aviation, Aeronautics, and Rocket Navigation in the Twentieth Century), entry 1, file 118. Article. Autograph and typescript with author's corrections, no date.

135. Fragmenty stat'i, posvyashchennoi kosmicheskim poletam (Fragments of an Article Devoted to Space Flight), entry 1, file 119. Autograph and typescript. no date.

136. Tablitsy, otnosyashchiesya k dvizheniyu rakety (Tables of Rocket Motion), entry 1, file 120. Autograph. No date.

137. Predislovie avtora (Author's Foreword), entry 1, file 121. Fragment of an article, autograph, no date.

138. Fragmenty statei, otnosyashchikhsya k voprosu o reaktivnykh letatel'nykh apparatakh (Fragments of Articles Dealing with Jet Aircraft), entry 1, file 122. Autograph, no date.

139. Reaktivnye pribory v issledovanii stratosfery (Jet Machines in Stratospheric Research). — Rabochaya Moskva, No. 51. 3 March, 1935.

140. Tol'ko li fantaziya? (Only Fantasy?).— Komsomol'skaya Pravda, No. 168. 23 July, 1935.

141. Polet v budushchee (Flight into the Future).— Kommuna, No. 184. Kaluga. 18 August, 1935 (with a portrait of the author).

142. Ot aerostata k zvezdoletu (From Aerostat to Starplane). — Pishchevaya Industriya, No. 127, Moskva. 2 September, 1935.

143. Fantaziya li zaatmosfernye polety? (Is Flight beyond the Atmosphere a Fantasy?).— Komsomol'skaya Pravda, No. 216. 18 September, 1935. 1 illustration and a portrait of the author.

EXPLANATORY LIST OF RUSSIAN ABBREVIATIONS

Abbreviation	Full Name (Transliterated)	English Translation
AIM	Artilleriiskii istoricheskii muzei	Historical Artillery Museum
ANTO MAI	Aviatsionnoe nauchno-tekhnicheskoe obshchestvo Moskovskogo aviatsionnogo instituta	Scientific and Technical Aviation Society of the Moscow Aviation Institute
Aviasektsiya Zakosoaviakhima	Aviatsionnaya sektsiya zakavkazskogo obshchestva sodeistviya oborone, aviatsionnomu i khimicheskomu stroitel'stvu	Aviation Section of the Transcaucasian Society for Promotion of Self-Defense and Aerochemical Industry
e. kh.	edinitsa khraneniya	storage number
GAORSS MO	Gosudarstvennyi arkhiv Oktyabr'skoi revolyutsii i sotsialisticheskogo stroitel'stva, Moskovskaya oblast'	State Archive of October Revolution and Post-Revolutionary Period, Moscow Region
GAU	Glavnoe artilleriiskoe upravlenie	Central Artillery Administration
GIRD	Gruppa izucheniya reaktivnogo dvizheniya	Jet Propulsion Study Group
GosAviaZavod	Gosudarstvennyi aviatsionnyi zavod	State Aircraft Plant
MVTU	Moskovskoe vysshee tekhnicheskoe uchilishche imeni N.E. Baumana	Moscow Higher Technical School im. N.E. Bauman
ODVF	Obshchestvo druzei vozdushnogo flota	Society of Friends of the Air Force
OSOAVIAKHIM	Obshchestvo sodeistviya oborone, aviatsionnomu i khimicheskomu stroitel'stvu	Society for Promotion of Self-Defense and Aerochemical Industry
OVI RKKA	Okruzhnoe voennoe izdatel'stvo Raboche-Krest'yanskoi Krasnoi Armii	District Military Publishing House of the Red Army
PRZ	Peterburgskoe raketnoe zavedenie	Petersburg Rocket Establishment
RKP	Rossiiskaya Kommunisticheskaya Partiya	Russian Communist Party

Abbreviation	Full Name (Transliterated)	English Translation
TsEKUBU	Tsentral'naya komissiya po uluchsheniyu byta uchenykh	Central Commission on the Improvement of the Living Conditions of Scientists
TsGA VMF	Tsentral'nyi gosudarstvennyi arkhiv voenno-morskogo flota	Central State Naval Archive
VSNKh	Vysshii sovet narodnogo khozyaistva	Supreme Council of National Economy